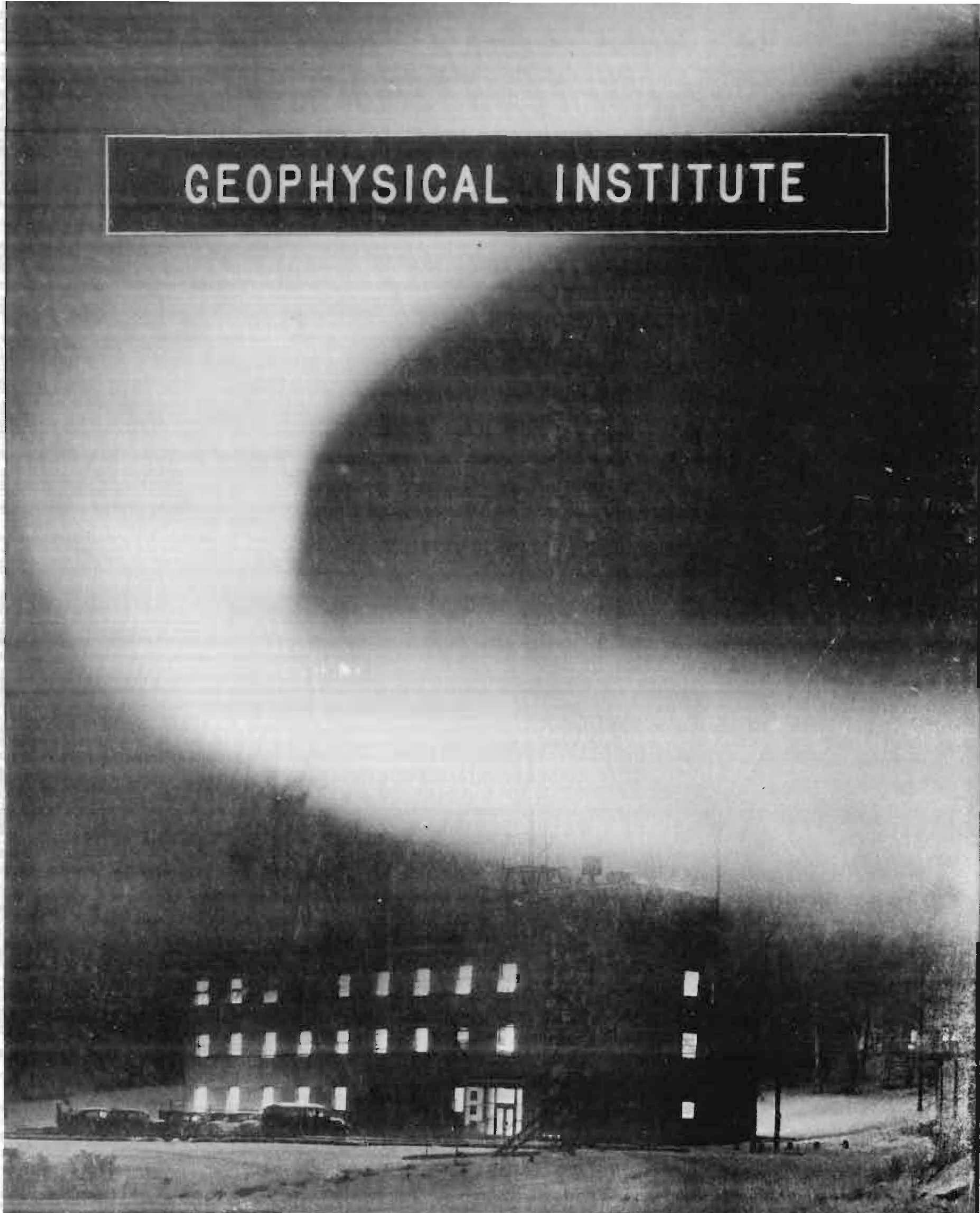

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Scientific Report No. 1

March 1, 1954, to March 31, 1955

AF 19(604) 1048

A Study on the Morphology of Magnetic Storms

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The research reported in this document has been sponsored by the Air Force Cambridge Research Center, Air Research and Development Command.

GEOPHYSICAL INSTITUTE

of the

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Sydney Chapman, Project Supervisor
Advisory Scientific Director of the Geophysical Institute

Report prepared by:

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(This thesis was submitted in April 1955 to the University of Alaska in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.)

C.T. Elvey, Director

Date Submitted:

April 20, 1955

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SUMMARY

The morphology of magnetic storms that has been investigated by S. Chapman since 1918 was further extended with more material as regards both the number of storms and the number of observatories. Three hundred and forty-six magnetic storms having sudden commencements were selected for the years 1902 to 1945. These 346 storms were classified by a new method based on the most notable characteristic of the storm-time variation observed in low and middle latitudes, namely, a world-wide diminution in the horizontal force; hence the maximum diminution in the horizontal force averaged over these latitudes was used as a measure to indicate the intensity of magnetic storms. The 346 storms here selected were classified into three intensity groups: (1) weak, (2) active, and (3) great storms. The numbers of storms classed in these categories are 136, 136 and 47, respectively. In the present thesis the investigation on the 136 weak magnetic storms is described. (In the previous study made by Chapman forty storms of moderate intensity were used.) The number of magnetic observatories used in the present study was also widely extended from eleven (in the previous work) to twenty-five. Seven observatories in the southern hemisphere distributed between geomagnetic latitudes 12° and 48° were included in these twenty-five observatories. The geomagnetic latitudes of the eighteen northern observatories range from 20° to 80°.

Several improvements were also made in the treatment of the magnetic data. One of the improvements is that hour-to-hour differences derived from the hourly values of the three magnetic elements, the horizontal force, declination and the vertical force, were used, instead of the ordinary hourly values as given in observatory reports.

With the 136 weak magnetic storms the storm-time variations of the three elements for the four pre-storm hours and the first seventy-two hours from the storm commencement were determined for eight groups of observatories, whose mean geomagnetic latitudes are 28° S, 21°, 28°, 42°, 52°, 59°, 65° and 80°; the first group being in the southern, the rest in the northern hemisphere. Thus the average features of the storm-time variations at various latitudes were able to be studied more closely. In determining these storm-time changes the daily variations on quiet days uncorrected for the non-cyclic variation were removed from the original data in order to allow for this latter variation.

Then the disturbance local-time inequality for the first, second and third storm days was examined for each magnetic element for each of the groups of observatories. The vectograms of these variations were also drawn. Besides confirming, on the whole, the views expressed in Chapman's discussions on the storm-time as well as the disturbance local-time inequality, the present results revealed more detailed features of these variations at various latitudes.

The disturbance local-time inequality for each element for each group of observatories was further studied for shorter intervals of storm-time, that is, for four 6-hour intervals in each of the first and second days and for three 8-hour intervals in the third storm day. The results were harmonically analyzed to determine the diurnal (24-hour) and the semi-diurnal (12-hour) components of these variations. The diurnal component was illustrated by harmonic dials, by which means the decay of the amplitude of these variations and the change of their phases with storm-time were clearly demonstrated. It was found that the phases of the disturbance diurnal equality in declination and the vertical force have certain definite relations with that in the horizontal force at each latitude, and that if the results for declination and the vertical force are combined with those for the horizontal force with some appropriate modifications in their amplitudes and phases, and if such averages are further combined among the groups of observatories in low and middle latitudes, the averaged harmonic dial so obtained is much more regular than those for individual elements or for smaller groups. The rates of growth and decay of the storm-time change and the disturbance local-time inequality were compared. The results indicate that these two variations vary at rates that are materially different in their course.

Detailed descriptions and discussions on these results, the final objects of the present study and plans for its future extension, are given in the present thesis.

The Morphology of Magnetic Storms

By M. Sugiura

Errata

Page 30, line 6, for 57° read 51°.

Page 36, in Fig. 2, Great Storms, for Season d read Season d-j.

Page 68, in Fig. 6, for 1(85°) read 1(80°).

Page 69, in Fig. 7, for 1(85°) read 1(80°).

Page 69, in Fig. 7, for 8(-20°) read 8(-28°).

Page 70, line 18, for are read is.

Page 73, in Fig. 8b, for GEOGRAPHIC N read MAGNETIC N, and
for MAGNETIC N read GEOGRAPHIC N.

1. Introduction.

Continuous magnetic observation shows that on some days the earth's magnetic field undergoes smooth and regular variations; while on other days their changes are more or less irregular. Days of the first kind are called magnetically quiet or calm days; days of the second kind are called magnetically active or disturbed days. On magnetically quiet days the regular variations consist of the solar and lunar daily variations, the former being predominant. On magnetically disturbed days the disturbance variations are superposed on these regular variations. The degree of magnetic activity or disturbance varies over a wide range from day to day and also at different latitudes. When a magnetic disturbance is extremely active, it is called a magnetic storm.

The study of the changing form of the magnetic storm field observed at various positions on the earth may be called the morphology of magnetic storms. In the description of the geomagnetic field and its changes it is often convenient to express the magnetic force by the three rectangular components: the horizontal force H, declination D and the vertical force Z. H is the magnitude of the horizontal component; D is the azimuth of the horizontal component reckoned positively from the geographical north towards the east, or negatively westwards from the north; Z is the vertical component, reckoned positive if downward, negative if upward. The symbol V is also used to denote the magnitude of the vertical force without regard to sign.

It has long been known that during magnetic storms H is reduced below its mean value. In 1861, J.A. Broun[1] already noticed this fact in his study of the horizontal force of the geomagnetic field;

his discussion was based on the daily mean values of H. In 1892, W.G. Adams(2) examined magnetograms taken at various observatories during the magnetic storms of 1880 August 11, 12 and 1885 June 24, 25. By a direct comparison of the several photographic records reduced to Greenwich mean time, he showed in a very marked manner that the character of a disturbance is similar over a very wide area of the earth's surface, and that the different phases of the disturbances take place at the different stations at nearly the same instant of time. Although such similarities are often striking, great differences between the effects of a storm on the magnetic variations at different stations are also frequently observed, indicating a complex nature of magnetic storms. The general features of magnetic storms can hardly be inferred by an examination of a small number of storms because of their irregularities; a statistical treatment of data is therefore inevitably required in the study on the morphology of magnetic storms.

The first statistical study on magnetic storms was made by N.A.F. Moos(3) in 1910; he studied the storm data obtained at Bombay. Although his work may now be only of a historical interest, an outline of his work will be given below. Since his original paper may be difficult to obtain, the author believes that such an attempt is not necessarily useless.

In the period 1872 to 1904 he found 113 storms having sudden commencements: such storms may be called sudden commencement (S.C.) storms (Moos called them X disturbances). These storms were fairly uniformly distributed over all the hours of the day. He divided the storms into three 11-year groups, 1872-1882, 1883-1893 and 1894-1904, one for each solar cycle, the number of storms in these three divisions being 38, 47 and 28, respectively. The twenty-four hourly values of H for the storms in each of the three divisions were so arranged as to have the hour nearest to the S.C. as the commencing hour, all in one line vertically coincident irrespective of their times in the day, the rest of the hours being arranged in 23 columns and each hour being reckoned from the commencing hour of the storm: it is convenient to refer to time so measured as storm-time. From such tables he determined the average departure of H during the first 24 hours of the storms from its mean value in the corresponding months. It was found that all three curves so obtained for the three divisions of the period clearly exhibit the same character of progression with storm-time. The variation obtained in this way may be called the storm-time variation in H; Moos called the curve showing this variation the character curve. The average storm-time variation (in H) for the whole period 1872 to 1904 was then determined, which gave a smoother curve than those for the three divisions. The average storm-time variation showed the following characteristics, viz., (1) a small initial rise of 26 gammas; (2) a large rapid fall which attained its lowest value of about 86 gammas below its initial value, indicating the maximum effect of the storm at about 10^h to 11^h (in storm-time); (3) this was followed by a slow recovery towards the mean; in the remaining 13 or 14 hours of the first day the recovery amounted to only 24 gammas. The hourly values of the 113 storms were then re-arranged, after being corrected for the aperiodic change, in the usual way for the derivation of the daily variation, separately for each of the three 11-year groups. The results show that the three daily variations so obtained bear a general resemblance to one another. The average curve of the three was also drawn. The average daily variation in H for <u>all</u> days for the corresponding period was then subtracted from them; the result, therefore, may be regarded as the disturbance daily variation for the average S.C. storm. He mentions that the average daily variation (for <u>all</u> days) may contain a fraction of the disturbance daily variation; but this fraction can probably be ignored. The disturbance daily variation so obtained shows that its maximum value is attained at about 6^h (local time) and its minimum at about 18^h.

He further proceeded to compare the average characteristics in H for great S.C. storms with those already described. For this purpose he selected 134 (S.C.) greatest storms in the period 1872 to 1904 (half of them being included in the 113 storms). The same method of analysis as was used in the study of the 113 storms was applied to these storms, separately for each of the three 11-year groups, and for the whole period. A remarkable parallelism in each pair of the corresponding curves for the two groups of storms was found; the magnitude of all variations is larger in the group of the 134 greatest storms than in the group of the 113 storms. The average storm-time variation in H for the 134 storms shows that H rises during the first hour, then falling rapidly by about 110 gammas in about 11 hours; this defect in H is recovered only by 16 gammas at the end of the first day. Two sets of the disturbance daily variations for the two groups of storms of the different intensities exhibit the same characteristics.

Moos further studied the storm-time variations for the second 24 hours of 29 selected storms. The result shows that the recovery in H, proceeding according to storm-time, which marked the latter part of the first day of the storms, was continued throughout the second day at a diminishing rate. The disturbance daily variations were also determined for these storms, but the results obtained there are not confirmed by later investigation.

The average non-cyclic change in H was then briefly discussed. "The average month may be regarded roughly to be made up of (1) a day of large disturbance which is characterised by a sudden dislocation of the magnetic conditions distinguished by an enormous negative aperiodic change in 24 hours (which may be more than 70 gammas); (2) a day or two less violently disturbed with somewhat smaller but positive aperiodic change which may be more than 40 gammas; (3) a large number of days of small disturbances which may have a small positive or negative aperiodic change; and (4) a few days of more or less quiet conditions but nearly always with a positive aperiodic change of about 4 gammas per day which though very small in comparison with the above figures, is large enough when compared with the actual secular change which in the average day is measured in tenths of one gamma." "During the minimum spot epoch, days of class (1) and (2) are usually absent and those of (3) and (4) predominate, and as a consequence the aperiodic change in the quiet days on the average, falls to about 2 gammas."

He then proceeded to discuss the difference curves of quiet days "accepted tentatively as free from disturbance" minus all days of the same epoch involving a disturbance factor. The magnetic records for eleven years, 1894 to 1904, were used for this study. The results show that such difference curves, in which the accidental irregular effects of storms are all smoothed and eliminated, are strikingly similar in character to the disturbance daily variations derived from the storm data, except of course in the amplitude. In both these results a simple diurnal harmonic component with a maximum at 6^h a.m. and a minimum at 6^h p.m., is clearly exhibited. This shows "indirectly in what exact relation do a heavy disturbed day, the average day, and the quiet day stand to one another."

The fact that most storms occur almost simultaneously all over the earth had been known for more than half a century. Having studied the storm-time and disturbance daily variations observed at Bombay, Moos next discussed the whole storm variation (the storm-time plus disturbance daily variation) for Bombay; he then compared the magnetic traces for H obtained at Bombay with those from Kew, Pavlovsk and Batavia for seven magnetic storms which commenced at different universal times. He pointed out: "In all these disturbances the accentuated effects of the local phase disturbance, which modifies the progression of the storm at each place, can be generally discerned." "If therefore it be true as suggested, that the sudden heavy accentuation in the amplitude of the diurnal wave is one of the principal features accompanying a disturbance, we may attempt to ascertain if an <u>average</u> storm in which the irregular oscillations are sufficiently smoothed can be regarded tò be made up mainly of two parts (1) a common pulse similar to the one referred to in paragraph 440 (in his paper), which commences everywhere simultaneously, takes on an average from 10 to 11 hours to attain its maximum effect and slowly to creep back to normal conditions, and (2) an accentuated diurnal wave depending at any place upon the position of the sun." He examined the records of the seven storms at Kew in a similar manner (for the first 24 hours), and compared with the corresponding records at Bombay.

A brief discussion was then given on the characteristics of the storm variations in declination and the vertical force for the 134 greatest storms. Disturbances do not affect declination and the vertical force at Bombay to any very large extent even during the greatest of storms. Nevertheless, the disturbance daily variations in these elements, when derived in the same way as for the horizontal force, so persistently exhibit their consistent characteristics that "one is inclined without much hesitation to accept them as denoting a real phenomenon."

The substantial part of Moos' discussions on magnetic storms was based on the analysis of records from Bombay alone. A more thorough investigation on the morphology of magnetic storms was made by S. Chapman with extensive data from many observatories, over a considerable range of latitude; his results and discussions are described in a series of papers published in 1918[4], 1927[5], 1935[6], and 1952[7]. (These papers will be referred to hereafter as 1, 2, 3 and 4, respectively.) The method of analysis used by Chapman is in principle almost identical with that used by Moos. The following quotation, however, may be made in this respect. In his paper 1, he refers to Moos' work: "...his (Moos') discussion has been of the greatest service in the present research, and the method of treatment of the data here adopted is almost identical with that first used by Dr. Moos. While I had independently decided upon similar lines of treatment before reading his work, the real stimulus to their application came from the discovery, made about the same time, of the success which had attended their use by Dr. Moos."

In order to show the state of our knowledge on the storm morphology at the time when the present work was planned and also to set forth the reasons why a new investigation was needed, the results obtained by Chapman will be described below.

In paper 1 he showed the storm-time variations (denoted by Dst) in H D, and Z for groups of stations as follows:

(1) Batavia, Porto Rico, Honolulu (22°)

(2) Zikawei, San Fernando, Cheltenham, Baldwin (40°)

(3) Pola, Potsdam, Greenwich (51°)

The numbers in parentheses give the mean magnetic latitude of the group. These variations were derived from the magnetic hourly data for the first 48 hours of forty selected storms of fairly uniform moderate intensity, the initial times being well distributed over the day. Since Batavia is in the south hemisphere, where the changes in Z and D are opposite to those in northern latitudes, the variations in these elements were reversed in combining them with those for other stations in the first group.

The storm-time variations showed that the initial rise and subsequent larger decrease in H, followed by slow recovery, occurs in all latitudes over the range considered, but that the maximum diminution decreased with increasing latitude.

The storm-time variation in V, that is, the magnitude of Z, is opposite to that in H, and much smaller in magnitude; unlike that in H, it is reversed in the southern hemisphere. There is practically no systematic storm-time variation in D.

A comparison was also made of the average storm-time variations in H at Bombay and Pavlovsk for three groups of storms selected according to their intensity, the storm data being the hourly values for the first 24 hours for Bombay and for the first 48 hours for Pavlovsk. The general character of the changes is the same in the three groups of storms, but the epoch of the maximum diminution in H is attained notably sooner in the more intense than in the moderate storms, and, in all groups, rather earlier for Bombay than for Pavlovsk.

The disturbance daily variations in H, D, and Z were derived from the first and second days of the forty magnetic storms; the variations will be called here SD for the first and second days. SD represents the daily variations on the storm days, less the average daily variation S for the corresponding months. S itself consists partly of the daily variation on quiet days Sq and partly of SD, so that when S was subtracted from the whole daily variation on the storm days, not only Sq but also part of SD were removed from it. Hence the disturbance daily variations obtained here represent most, but not quite all, of the SD variations on these days of storm.

Chapman showed five sets of curves indicating Sq (with a certain admixture of SD) and SD (for the first and second days) for Sitka (61°), Pavlovsk (58°), Pola, Potsdam, and Greenwich combined (51°), and the groups (2) (40°) and (3), (22°) which have already been referred to. It is clear that SD is quite different in type from Sq. For example, in Sq for H, there is a reversal of type at about magnetic latitude 30°, while in SD for H, though also a reversal of type, it occurs between latitudes 58° and 51° (probably at about 55°). In Sq, the extreme departures from the mean occur in the middle of the day; whereas SD passes through the zero level at that time. Differences between Sq and SD are also seen in Z and D, though they are of different kind from H. In all the three elements, SD for the second day is smaller than for the first day, indicating a decline in SD after the first day of the storm.

The most remarkable feature of SD is the great increase of SD in Z on passing from the equator to Pavlovsk and Sitka. The S variations for Pavlovsk and Sitka may therefore be expected to contain a relatively greater amount of the SD variation than those for lower latitudes; the type of the Sq variations at these stations supports this expectation.

It is important to ascertain whether the slight magnetic disturbance which distinguishes the average day from specially quiet days differs from intense disturbance not only in degree but also in type. This can be tested by a comparison of SD during storms with the daily variation as derived from all days. Chapman (2) examined such daily variations for Sitka, Pavlovsk, Greenwich, Cheltenham, and Honolulu. It became clear that SD preserves essentially the same character while the intensity of disturbance ranges from storms down to the slight disturbance present on ordinary days. In this respect B. Cynk[8] confirmed this view by using more data and also showed changes in SD with season.

As we have seen, during magnetic storms there are two systematic changes, one depending on storm-time and the other on local time. Therefore, the question of the similarity of type as between intense and weak disturbance may be raised also in regard to the storm-time variation; unfortunately, however, with respect to the storm-time variation, this cannot be tested as was done in SD; the reason for this is that in the case of minor disturbance the determination of storm-time reckoned from the beginning of the disturbance is not possible as it is in storms that commence with abrupt changes in all the three elements. Moreover, it is usually hard to distinguish whether a prolonged period of minor disturbance is made up of one or of many individual disturbances.

The local-time changes considered before are measured from the daily mean value of the magnetic element as origin; they are independent of the absolute value of this mean. The storm-time changes, on the other hand, directly affect the daily mean value. Therefore, it may reasonably be assumed that, when the average daily mean of a large number of more or less disturbed days is considered, it represents the mean storm-time effect Dm. During the first few hours of a magnetic storm, H generally rises, and subsequently experiences a much larger and more prolonged decrease, which recovers only very slowly. Thus the average Dm in H should be a decrease in the daily mean during disturbance.

The storm-time variation in Z is much smaller, and opposite in sign, compared with that in H; Dm in Z, therefore, should be a very slight increase in moderate northern latitudes; the effect should vanish at the equator and be reversed in the southern hemisphere. Declination shows no systematic average storm-time change in low and middle latitudes; therefore Dm for D should be very small and not systematic.

These expectations were tested by observational data for the five stations used for the study on SD for minor disturbances. The changes observed are small except in H, where they are systematic, and in good agreement with the expectation. This evidence favors the view that also as regards the storm-time changes slight and intense disturbances are similar in type.

Thus it appears that the disturbing magnetic field, which is superimposed on the main magnetic field of the earth and the varying field manifested by the daily variations on quiet days, maintains its definite average characteristics in regard to both its spacial and temporal changes, over a wide range of the degree of disturbance. This conclusion, however, relates to world-wide magnetic disturbance and not to local disturbances.

The discussions given so far are restricted to latitudes up to about 60°. Mere inspection of magnetograms obtained at stations in higher latitudes reveals that magnetic disturbances there are more complex than in lower latitudes. The observational material is more limited for these high latitudes; consequently, forty or more storm days were not available for the study of the storm-time and disturbance daily variations, analogous to those determined for lower latitudes. An attempt was made, therefore, to obtain the average characteristics of Dst and DS in polar latitudes in the same way as was done in the case of slight disturbance for lower latitudes. The results will, of course, have reference to the relatively low degree of disturbance.

The average effect of Dst was studied by taking the difference between the daily mean values of the magnetic elements on all days and on quiet days. The data used by Chapman consisted of expeditions of 1882-3, the results of later Antarctic expeditions, and the hourly values for 1914 and 1915 recorded at Sodankylä (a little to the South of the auroral zone). The results obtained from these data may not be strictly comparable among each other, but suffice for the present purpose.

From the examination of records for H at ten observatories, it was found that, on the whole, the horizontal disturbance vectors, as determined from the all-day minus quiet-day means, diverge from a point or small region near the center of the zone of maximum auroral frequency (which center is also the geomagnetic axis pole) determined by H. Fritz[9]; their distribution is not symmetrical about the geographical pole. The mean storm-effect in the horizontal force, therefore, is considered as a reduction in its component along the magnetic meridian (the meridians through the magnetic axis); in this respect it resembles the Dm in lower latitudes. The magnitude of the reduction in H, however, is much larger in polar regions than in low latitudes; it ranges up to about 20 gammas, whereas the corresponding magnitude at the equator is about 10 gammas. Summarizing the average storm-time variation in the horizontal plane at various latitudes, it is described in the following way. It is a decrease everywhere; its numerical value has a maximum at the equator, and decreases towards a minimum at about 60° latitude, then increasing rapidly towards the auroral zone.

When this study was made, the data for the vertical force were scanty, because not all the polar stations of 1882-3 were equipped with reliable (or any) vertical force magnetographs. It was found, however, from the available data that at Fort Rae (69°)*, Nova Zembla (64°) and Kingua Fjord (78°) the all-day mean for Z is distinctly

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* The numbers in brackets are the geomagnetic latitudes.

higher than the quiet-day mean, by about 18, 18 and 16 gammas, respectively. At Bossekop (67°), Sodankylä (64°), and Sitka (60°) the change is negative and small, viz., -4, -4, and -3 gammas. At Cap Thordsen (75°) and Jan Mayen (73°) the change appears to be small. Thus, the average storm-time variation in the vertical force is summarized in the following way. It is small and positive from the equator (where the change is zero) up to about 55° northern latitude; there it changes sign and increases (numerically) towards the auroral zone. A further change of sign, to positive values, occurs at or within the auroral zone, where the large values already noted are found. In the study made by E.H. Vestine and S. Chapman[(10)] with the material obtained during the Second International Polar Year, 1932-3, it is shown that farther within the auroral zone the differences (all-days minus quiet-days) decrease again towards the axis of magnetization of the earth. (They also studied the variation in H within the zone.)

Similar results were shown by C. Chree[(11)] for Cape Evans (83° S); the numerical value of the vertical force increases during disturbances within the southern auroral zone.

The local-time (daily) disturbance variations in high latitude will now be considered. As has already been described, the local-time disturbance variation in the vertical force preserves its phase from the equator up to Sitka (60°) with a morning minimum and an afternoon maximum; the amplitude increases greatly with increasing latitude. At Sitka the range is about 20 gammas; it continues to increase to Bossekop (67°) where it exceeds 100 gammas. Chapman showed the curves for the annual mean daily variations of the vertical force for Bossekop (67°), Nova Zembla (64°), Jan Mayen (73°), Point Barrow (69°), Fort Rae (69°), Cap Thordsen (75°), and Kingua Fjord (78°). All these curves except for Nova Zembla are of very large range. The most remarkable feature is that all the curves for the stations to the north of Nova Zembla show opposite phases to that for Bossekop (and the stations in lower latitudes). The curve for Nova Zembla is transitional between the two types, the range being much smaller than those for the other six stations. The reversal of phase appears to occur within a narrow belt of magnetic latitude of adjacent to the auroral zone. It is known(12) that the auroral zone broadens and moves towards the equator during periods of intense disturbance. Then, a station which ordinarily is on the equatorial side of the zone may during magnetic storms be under, or on the polar side of, the zone. If so, the disturbance changes in the magnetic field at the station during slight disturbance may be radically different from those during magnetic storms, even though, in relation to the zone, the character of the disturbance field itself may be similar in the two cases. This possibility is exemplified by Nova Zembla; if records from this station on individual days are examined, on some days, the variation in Z has a morning maximum and an afternoon minimum, while on other days it has a reverse phase.

The SD variations (all-days minus quiet-days) in the horizontal plane are also very large, the range being of the order of 50 gammas. In passing northwards from Sitka to the polar cap, the daily variation of the force in the horizontal plane undergoes a remarkable change of type. This change is best shown by the vector diagrams for the horizontal-force SD variation. The vector diagram is the curve traced by a vector with a fixed origin, representing in magnitude and direction the horizontal component of the force; that is, it combines the variations in the two perpendicular components, H and D (the force component perpendicular to H). Chapman has proposed to call such vector diagrams vectograms. The vectogram for Sitka bears some slight resemblance to the roughly oval form, elongated in the direction transverse to the magnetic meridian, shown at Greenwich and other stations in similar latitudes. But for stations quite near to the auroral zone the vectograms are very narrow in the direction parallel to the zone; this character is well exhibited by the vectograms for Nova Zembla (64^o), Sodankylä (64^o), and Bossekop (67^o). At these stations the maximum poleward force occurs at about 16^h or 18^h, and the minimum at about 2^h. On passing well inside the zone the vectogram becomes nearly circular; this is illustrated by the vectograms for Kingua Fjord (78^oN) and Cape Evans (83^oS).

The average characteristics of disturbances in polar regions so far considered are those associated with relatively slight disturbance; but the distribution and development of the additional disturbance field in polar regions, as well as in lower latitudes, remain fairly constant and independent of the intensity of the disturbance.

The general features of the D field observed at various latitudes have been described above. Harmonic analysis of this field shows that its origin, like that of Sq, is partly external and partly internal. The internal part can reasonably be explained as due to electric currents induced within the earth by the external part of the D field. The origin of the external field is unknown, though there is good evidence that the field near the auroral zone is due to strong currents flowing along the zone at a height of about 100 Km above the ground.(10)(13)

The form and position of the electric current-system flowing above the earth's surface cannot be inferred uniquely from a knowledge of the distribution of the disturbance-field at the earth's surface. Kr. Birkeland[14] believed that electric current came into the auroral zone from outer space, approximately along the earth's lines of magnetic force, and that it left the earth again, along the lines of force, after flowing along the zone for some distance. Vestine and Chapman[10] showed that the observational facts do not favour Birkeland's view. According to Chapman, the electric currents responsible for the disturbance field flow in our atmosphere. Since their direction is not the same all around the auroral zone, they must complete their paths outside the zone, but in the atmosphere. He proposed, in paper 3, the electric current-systems that can explain the observed storm field. In his current-systems the principal features are intense currents across the polar cap within the auroral zone, which complete their circuits partly by westward flow along the auroral zone and partly (to a less extent) eastward along the zone. For moderate magnetic storms he estimated that the westward flow reaches a maximum intensity of 350,000 amperes on the dawn meridian; the eastward flow attains its maximum intensity of 200,000 amperes on sunset meridian. Between the (northern and southern) auroral zones a total current of 500.000 amperes crosses the sunset meridian, partly completing its circuit by eastward flow in or near the auroral zone, but mainly (300,000 amperes) encircling the earth.

Vestine and his colleagues[15] compared the current systems derived by Chapman with those determined from four individual storms observed during the Second International Polar Year 1932-3. They drew the current systems for individual hours for the storms, and showed that the polar disturbance field for individual hours of storm undergoes systematic changes with time. But, in general, these systems closely resemble those found from the average characteristics of the field, although there may be considerable variability from hour to hour during an individual storm. They also suggested a possibility of the presence of important seasonal change in the character of the polar disturbance field.

In paper 1, Chapman showed the local-time disturbance variations for the first and second days of the average magnetic storm. In the extension of his study, described in paper 4, he examined the local-time disturbance variations for shorter intervals of storm-time for eight observatories in geomagnetic latitudes not exceeding 50°. In this way the variation was considered as a function of storm-time, as well as of local-time. The decrease in the amplitude of SD_2 as compared with SD_1, is analogous to the decline in Dst in the second as compared with the first storm day. In Dst the method of analysis enables the change to be followed continuously, whereas in the case of SD, the method of analysis used in paper 1 gives the change in SD only from one day to the next, that is, in the mean, from storm-time 12^h to 36^h. This does not of course imply that SD changed suddenly from the first to the second day. The variation must be continuous throughout a magnetic storm. It is not a true daily variation like Sq; for example, in the case of the most intense storms, whose active period may be less than a day, it must die away, with Dst, in a duration shorter than a day.

Nevertheless, during weak disturbance, as investigated in paper 2, this change manifests itself as an addition to Sq, varying in intensity in rough parallelism with the degree of magnetic activity. In this sense the name "disturbance daily variation" and the symbol SD are appropriate. It is also possible, however, to determine the part of the storm variation that changes with local time, for any intervals having a definite beginning and a limited duration. For the variation so determined the name "disturbance daily variation" is not appropriate; Chapman adopted for it the name "disturbance local-time inequality", and the symbol DS, where D as in Dst, denotes disturbance, and S refers to position relative to the meridian containing the sun, as measured by the local time.

Chapman determined harmonic coefficients of DS for the first four half days of 40 moderate storms. The diurnal harmonic components of DS were illustrated by means of harmonic dials. In such dials are plotted the points representing the end of a vector drawn from the origin, with length equal to the amplitude and with the direction specified by the phase. It was shown in the harmonic dial for H that the amplitude of DS(H) is greatest for the first half day, and steadily diminishes from each half day to the next, while the phase steadily increases. The dials for E and V show a similar change, but the phase for E is about 90° and for V is about 180°, greater than for H, on corresponding half days. As to the relative size of DS, it is greatest in H, and least for V. For the elements H and E, harmonic coefficients of the diurnal component of DS were determined for 4-hour intervals. On the harmonic dial for DS(H) drawn with these coefficients, the results for DS(E) were plotted after modification in two respects:

(1) the phase is decreased by 90°, (2) magnification to render the amplitude in E comparable to that in H. Taking the mid points of H and E, a smooth curve was drawn to show the continuous change of DS.

The variation of DS during the first four hours from the storm commencement was further studied for H and E. With the results for DS(H) and Dst(H), he compared the rates of growth and decay of these two variations. It was shown that DS(H) follows a course very different from that of Dst(H); DS(H) attains its maximum earlier, and then decreases much more rapidly.

The substantial part of the material for 1, 2, 3, and 4 is composed of hourly magnetic data from eleven observatories (eight observatories in the case of 4) during the first 48-hour period of 40 magnetic storms of moderate intensity in the years 1902 to 1911. Although much more could be abstracted from the same material as for papers 1 to 4, it was thought desirable at this stage to make a new and more thorough investigation of the magnetic storm morphology, using considerably more extensive data, as regards both the number of storms and the number of observatories. Among the subjects to be studied are the general features of Dst and DS in high latitudes, data for which were scanty when the previous studies were made, and the effects of season and storm intensity on the morphology of storms. These subjects will be discussed in a series of papers of which the present paper forms the first part.

In this thesis the average features of the storm-time variation and the disturbance local-time inequality of 136 weak magnetic storms will be described. The period from which these storms were selected and the number of observatories used here are much more extensive than any of the similar studies so far made. Several improvements are also made in this work in the selection and classification of storms and in the treatment of the data. Although remarkable seasonal changes were found in DS for high latitudes, these changes will not be discussed here. Besides Dst and DS, there are irregular variations peculiar to each individual storm; but such irregular variations are not considered in this paper.

2. Selection of magnetic storms.

In the study on the morphology of magnetic storms made by Chapman, 40 selected storms of fairly uniform moderate intensity were used. (Particulars for these storms are not given in papers 1, 2, and 3; but they are given in Table 1 in paper 4.) They were selected from those with sudden commencements, contained either in a list compiled by E.W. Maunder from the Greenwich records up to 1903, or (for later years) from the publications of the U.S. Coast and Geodetic Survey for the observatories of Honolulu, Cheltenham and Sitka. They were chosen as being all of moderate intensity.

In Moos' work on magnetic storms already referred to in Section 1, he first made a table of disturbances, in which the daily mean of H* is lowered by 50 gammas or more; this table was supplemented (originally for a different purpose) by another table of disturbances selected by a simple inspection of the traces for H. In the latter are listed all the disturbances that lasted for five hours or more, and indicated an abnormal movement in range greater than 70 gammas. From these tables of disturbances he selected 113 S.C. storms of varying degree of intensity. His 134 greatest S.C. storms were also selected from those listed in the two tables.

In the present work it was intended to select as many magnetic storms as possible; the selection is such that all the sudden commencement storms of various intensities are included regardless of their type and duration. Thus, all storms from the extremely weak to the greatest are intended to be included in this study. The period from which magnetic storms are to be chosen must be decided having regard to the following two factors: (1) the availability of magnetic hourly

* At Bombay Observatory.

records from a sufficient number of observatories; (2) it should include several sunspot cycles to study changes in characteristics of storms with the sunspot cycle. In order to meet these requirements, the years 1902 to 1945 were chosen, covering approximately four complete solar cycles.

First, a list of magnetic storms was made, based on (a) lists of principal magnetic disturbances given in reports of the U.S. Coast and Geodetic Survey for Magnetic Observatories at Cheltenham, Tucson, Porto Rico and Honolulu; (b) descriptions of "principal magnetic storms" given in the journal Terrestrial Magnetism and Atmospheric Electricity; (c) a list compiled by Maunder[16] from the Greenwich records up to 1903; (d) catalogues of magnetic storms and sunspots for the years 1874 to 1927 given in the Greenwich Photo-Heliographic Results for the year 1927, and (e) later reports by H.W. Newton in the Observatory. Of these magnetic storms all those were taken for which two or more observatories reported sudden commencements with a reasonable agreement in time; 346 magnetic storms of various intensities were thus chosen in the period 1902 to 1945. It should be noted that after these storms were once selected no further selection was made according to their types; no inspection was made of the magnetograms for the storms. When two or more storms occurred in close succession, they were regarded as separate individual storms. Though all possible care was taken in the selection of these storms and in the determination of the times of sudden commencements, there may inevitably be some questionable cases specially in weak storms, when magnetograms for individual stations are inspected. However, the statistical results obtained here would not be affected by a few such cases.

3. Observatories used in the present study.

The data used here refer to 25 observatories, of which particulars are listed in Table 1. Compared with the eleven or eight observatories used in papers 1 to 4, the number of observatories was greatly extended;

Table 1. Observatories*; their geographic (gg) coordinates and geomagnetic (gm) latitudes, and the number of years for which data were available. The southern latitudes are indicated by negative sign.

	Observatory	Latitude gm	Latitude gg	Longitude (gg) Angle	Longitude (gg) Time	Number of Years
1.	Godhavn	80°	69°	307° E	20.5h E	20
2.	Tromsö	67	70	19	1.3	16
3.	Sodankylä	64	67	27	1.8	29
4.	Lerwick	63	60	359	23.9	12
5.	Sitka	60	57	225	15.0	44
6.	Eskdalemuir	59	55	357	23.8	25
7.	Lovö	58	59	18	1.2	18
8.	Rude Skov	56	56	12	0.8	19
9.	De Bilt	54	53	7	0.5	44
10.	Greenwich	54	51	0	0.0	44
11.	Val Joyeux	50	48	2	0.1	44
12.	Cheltenham	50	39	283	18.9	44
13.	Ebro	44	41	1	0.1	26
14.	Tucson	40	32	249	16.6	36
15.	Porto Rico	30	18	294	19.6	43
16.	Kakioka	26	36	140	9.3	37
17.	Honolulu	21	21	202	13.5	44
18.	Zikawei	20	31	121	8.1	35
19.	Rio de Janeiro	-12	-22	316	21.1	31
20.	Apia	-16	-14	188	12.5	11
21.	Batavia	-18	-6	107	7.1	35
22.	Cape Town	-33	-34	19	1.3	13
23.	Watheroo	-42	-30	116	7.7	27
24.	Toolangi	-47	-38	146	9.7	10
25.	Christchurch	-48	-44	173	11.5	18
					TOTAL	725

* When one observatory was succeeded by another, only one of them is referred in Table 1 and also throughout this paper; but gg coordinates and gm latitudes are the averages of the continuing observatories; e.g. Greenwich-Abinger, Val Joyeux-Chambon la Foret, etc. are represented by Greenwich, Val Joyeux, etc., respectively.

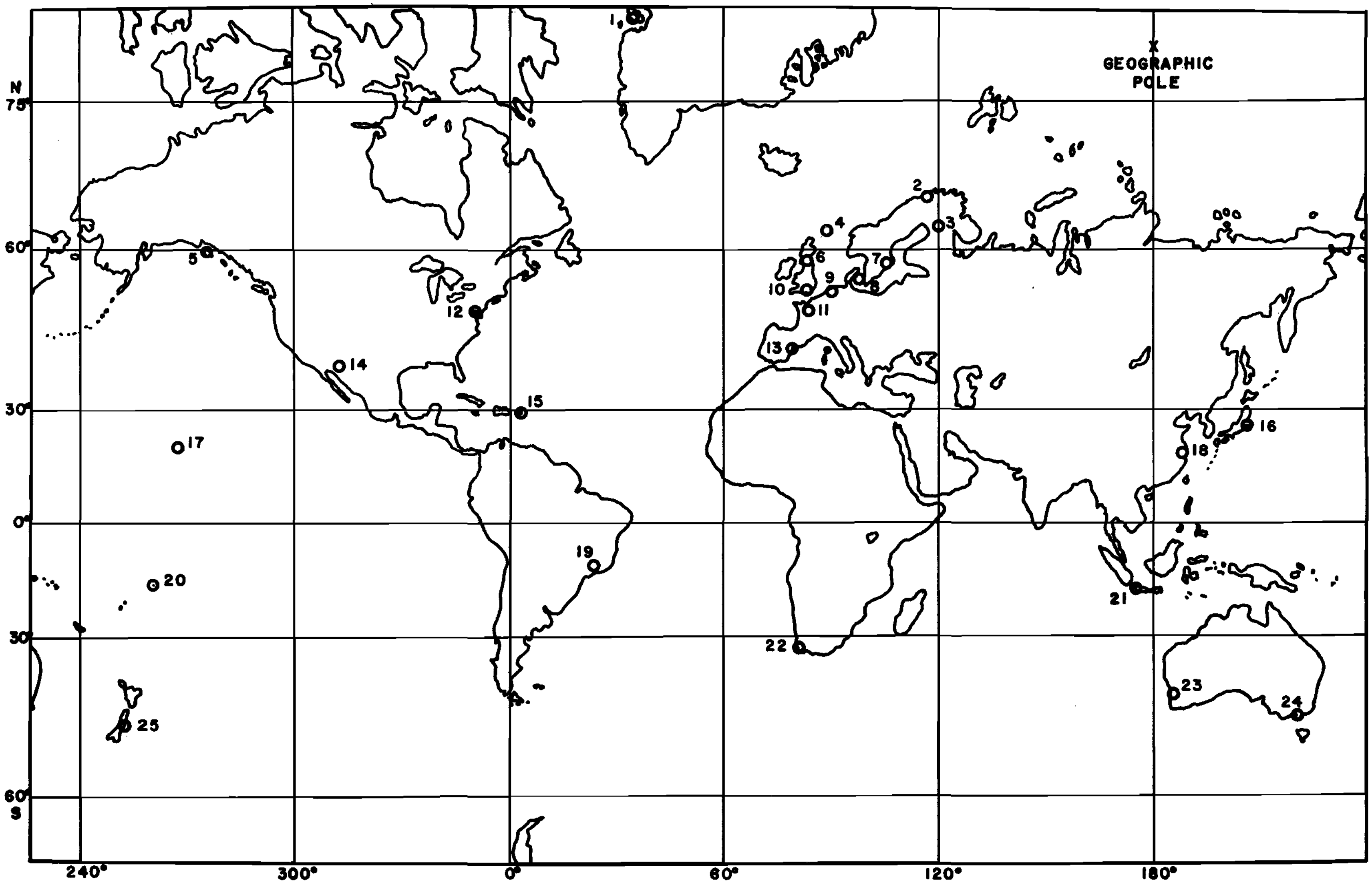

Fig. 1. Distribution of observatories; geomagnetic coordinates

seven southern stations are included, though the data are much less complete for them than for most of the northern stations. In the last column of Table 1 is geven the number of years for which magnetic storm data were available; they are given to compare the statistical importance of these observatories. The total number of observatory years used in this study is 725. The distribution of the observatories over the earth is shown in Fig. 1. The stations are most densely distributed from 20° N. to 60° N. One of the important improvements made in this work is that the storm data for stations near or in the auroral zone and also in the polar cap were analyzed as well as for the stations in lower latitudes.

4. Classification of magnetic storms.

As has already been mentioned, in papers 1 to 4, 40 storms of "moderate intensity" were used. It was shown in 1 that the storm-time variation in H is characterized by the initial rise and subsequent large decrease, followed by slow recovery, in all latitudes over the range considered in that paper (22° to 57°), and that the maximum diminution decreased with increasing latitude. In the higher latitudes the irregular variations increase relatively to the average storm-time variation, and render the latter more difficult to be determined.

In this paper the characteristics of Dst in H described above were used for the classification of magnetic storms. That is, storms were classified by the magnitude of maximum diminution in H in low and middle latitudes.* For the classification it would of course be possible to use measures of magnetic activity such as the international character-figure C,[17] the u-measure,[18] the three-hour range index K,[19] or the planetary magnetic three-hour range index Kp.[20] These character figures are defined in the following way. (1) In 1906 the need for a numerical representation of the activity of the geomagnetic field led some 30 magnetic observatories to cooperate by assigning to each day one of three characters, namely: "0" for quiet days, "1" for moderately disturbed, and "2" for seriously disturbed days. Though this characterization is crude, the average of the 30 independent estimates for each day affords a valuable measure for the daily activity. (2) The inter-diurnal variability U of the horizontal intensity H for any station P is defined as the difference between the mean values of H

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* Throughout this paper the latitudes are geomagnetic latitudes unless geographical latitude is expressly indicated.

for a particular day and for the preceding day, taken without regard to sign. Its average amount depends on the (geomagnetic) latitude or north-polar distance (Θ); an equatorial value u of the inter-diurnal variability is obtained by taking the mean of $U/\sin\Theta\cos\psi$ for a number of observatories, where ψ denotes the angle between the direction of H at P, and the great circle passing through P and the magnetic-axis poles; the division by $\sin\Theta\cos\psi$ is made in order to base u on the component H parallel to the earth's magnetic axis. This equatorial value u, expressed in units of 10 gammas, is taken as a measure of the magnetic activity. (3) In connection with direct ionospheric studies by radio methods, it was found necessary to provide a new scheme using smaller time-units than the day which is used for the international character-figure C. The three-hour-range index K, based on the "Potsdamer erdmagnetische Kennziffer" (described by J. Bartels in Zs. Geophysik, 14, 1938) was therefore adopted by the International Association of Terrestrial Magnetism and Electricity in 1939. This index was intended to characterize the variation in the degree of irregular magnetic activity throughout each day. Each collaborating observatory assigns to each of the three-hour intervals beginning with the Greenwich mean time 0^h, 3^h, 6^h, ----, 21^h, a value of K, consisting of one of the integers 0 to 9, as follows: For each observatory, a permanent scale is adopted once for all, giving the limits within which the ranges R, measured in units of force, gammas, define the index K. The range R for each magnetic element is defined as the difference between the highest and lowest deviation, within the three-hour interval, from a smooth curve (a regular daily variation) to be expected for that element on a magnetically quiet day, according to the season, the sunspot cycle, and, in some cases, the phase of the Moon. Only the largest of the three values R for each interval, that is, R for the most disturbed element, is taken as the basis of K; the two smaller ranges do not enter further. (4) The planetary index Kp is described in I.U.G.G. Association of Terrestrial Magnetism and Electricity, Bull. No. 12b. p. 105, 1949. This index is probably the best measure of particle activity from solar causes. A table of planetary indices Kp appeared for the first time in the Journal of Geophysical Research, Vol. 54, p. 295, 1949.

Though these indices express the degree of magnetic activity in their own ways, they are not necessarily suitable for a measure indicating the intensity of magnetic storms. The international character-figure C is too crude to classify magnetic storms. The u-measure may be useful, when averaged over a month or a year, to see the average amount of one aspect of magnetic disturbance during the corresponding periods, but it is not appropriate as a measure for a single day. K-indices indicate the degree of disturbance for short intervals, but they are not necessarily convenient for the classification of magnetic storms. The possibility of using the planetary index Kp, however, was considered, when the classification of storms was planned; but Kp-indices are not available for the most part of the period used in this work.

Hence it was decided to attempt to classify storms by a new method based on the magnitude of the maximum diminution in the smoothed curve for H in low and middle latitudes. When daily means of the horizontal force as reckoned from pre-storm level were plotted against universal time for various observatories in these latitudes, a remarkable similarity was found in their general type. If a sufficient number of observatories distributed uniformly along a parallel of latitude are used for such plots, the mean of the curves will represent the actual course of the symmetrical part of the storm-field for the latitude. If such curves are further averaged over low latitudes, the maximum departure of the resultant curve from its pre-storm level will provide a good measure for storm intensity. This method of classification, however, meets some difficulties when applied to a practical problem. First, the number of observatories in low latitudes does not suffice for this purpose. Secondly, it is not convenient to determine the mean curve from plotted daily means in each case, when, as in the present study, a large number of storms are dealt with. The first difficulty was removed by extending the range to middle latitudes. This should not introduce any significant departure from what was originally aimed at. The second problem was solved on a statistical basis by a suitable assumption as to the time of minimum H. The method adopted here will now be described.

For each observatory, the day on which a magnetic storm commenced is named day 0, and days are numbered -1, -2, ..., etc., backwards, and 1, 2, ..., etc., forwards from it. These day numbers may refer to local time or G.M.T. according as daily means refer to the local or Greenwich day. It is assumed that pre-storm level and minimum H are represented by the daily mean values of H for day -1 and day 1, respectively. The index for the magnetic storm intensity, which is here called the class number, is defined as the daily mean H, as expressed in the unit of gamma, for day -1 minus that for day 1. The class number so defined was assigned to each of the 346 magnetic storms.

By the definition the class number is positive in the majority of cases. But some very weak storms gave negative class numbers. This is due either to a low value of the daily mean for day -1 on account of an aftereffect of a preceding disturbance, or to the fact that minimum H was attained earlier than day 1, or much delayed, and that the level of day -1 is lower than that of day 1. All these cases were examined individually, and pre-storm level and minimum H were re-defined in each case. The class numbers so derived were then all positive. Besides these very weak storms, there are some cases, mostly among great storms, in which the class number appeared faulty because of the minimum H being reached on day 0 or 2, instead of day 1. In such cases, the daily mean for the day on which minimum H was attained was substituted for the daily mean for day 1.

Particulars of magnetic storms, times of their sudden commencements (G.M.T.), and their class numbers are listed in Table 2 at the end of this Section. These storms were classified into three groups, weak, active, and great magnetic storms, according to the following criteria:

	Class Number
Weak magnetic storms	0 to 30
Active magnetic storms	31 to 60
Great magnetic storms	greater than 60

Groups of weak and active storms were divided into three seasonal subgroups: December solstice (November to February) (d), June solstice (May to August) (j), and equinox (March, April, September, October) (e). Great storms were divided into two seasonal subgroups: solstice (November to February and May to August) (d-j) and equinox (March, April, September, October) (e). The number of magnetic storms belonging to each subgroup is listed in Table 3. In the group of active storms, 8 storms were transferred from e to j; in the group of great storms 6 were transferred from d-j to e, in order to equalize the number of

Table 3. The number of storms in intensity-season subgroups.

	Solstice		Equinox	Total
	d	j	e	
1. Weak storms	42	50	44	136
2. Active storms	46	40	50	136
3. Great storms	37		37	74
Total	215		131	346

storms in the subgroups. The distribution of storms over the Greenwich day is shown in Fig. 2 for the seasonal subgroups and for the combined whole year group for each intensity. It can be seen that the storms are distributed fairly uniformly over the Greenwich day in all cases.

Out of the forty storms selected by Chapman (1) thirteen were found to be classified by the present method as weak storms and are included in the present analysis; twenty-five were classified as active, and two as great storms.

In Fig. 3a are plotted for each year the number of sudden commencement storms chosen here, the annual mean class number and the annual mean sunspot number based on the monthly mean sunspot numbers published from Zurich. It is of interest thus to see how the number of magnetic storms and the mean class number are influenced by the sunspot cycle. Fig. 3b shows the changes in the number of storms per year and in the annual mean class number, averaged over four solar cycles. The number

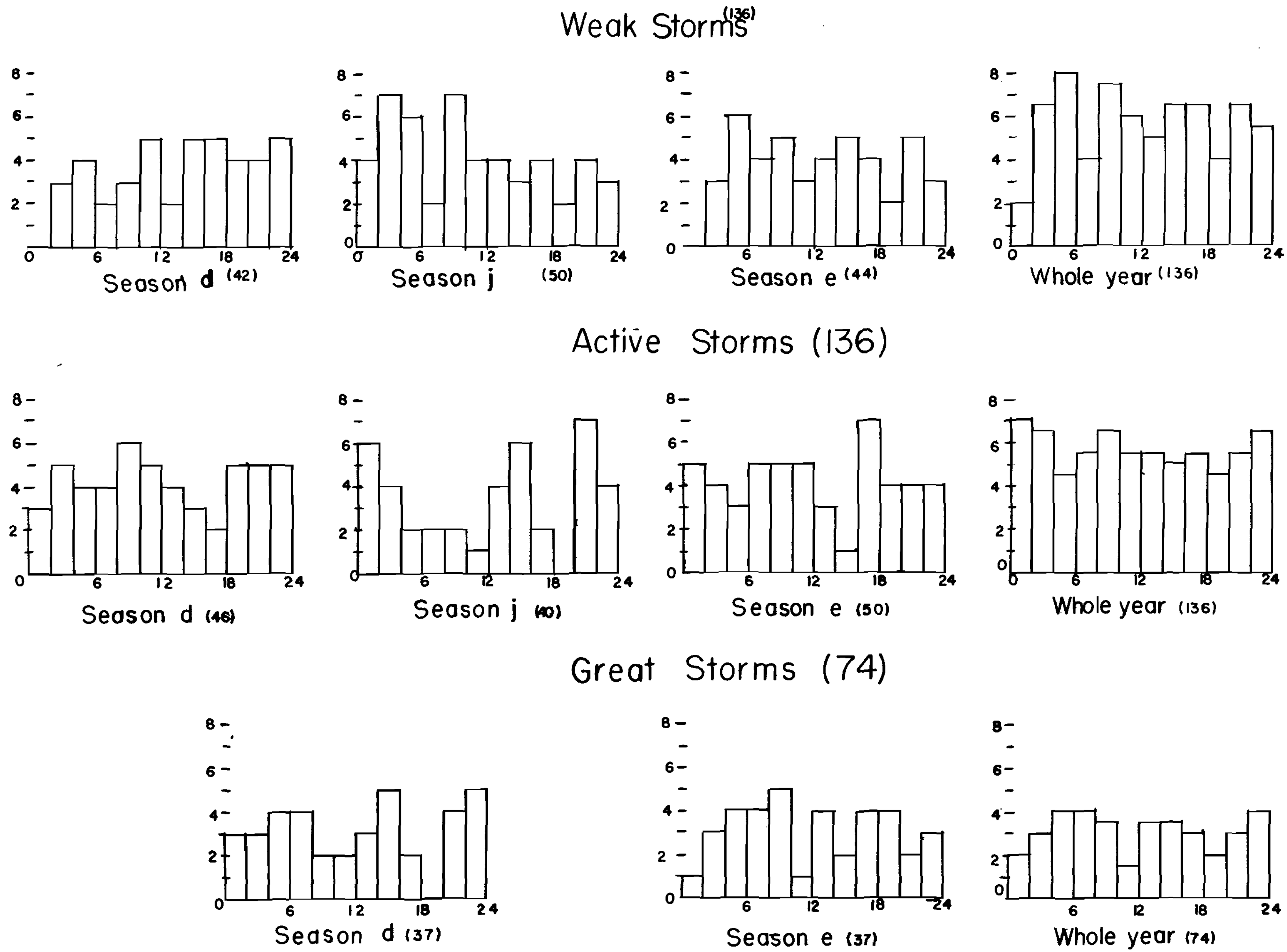

fig 2 Distribution of Magnetic Storms over Greenwich Day

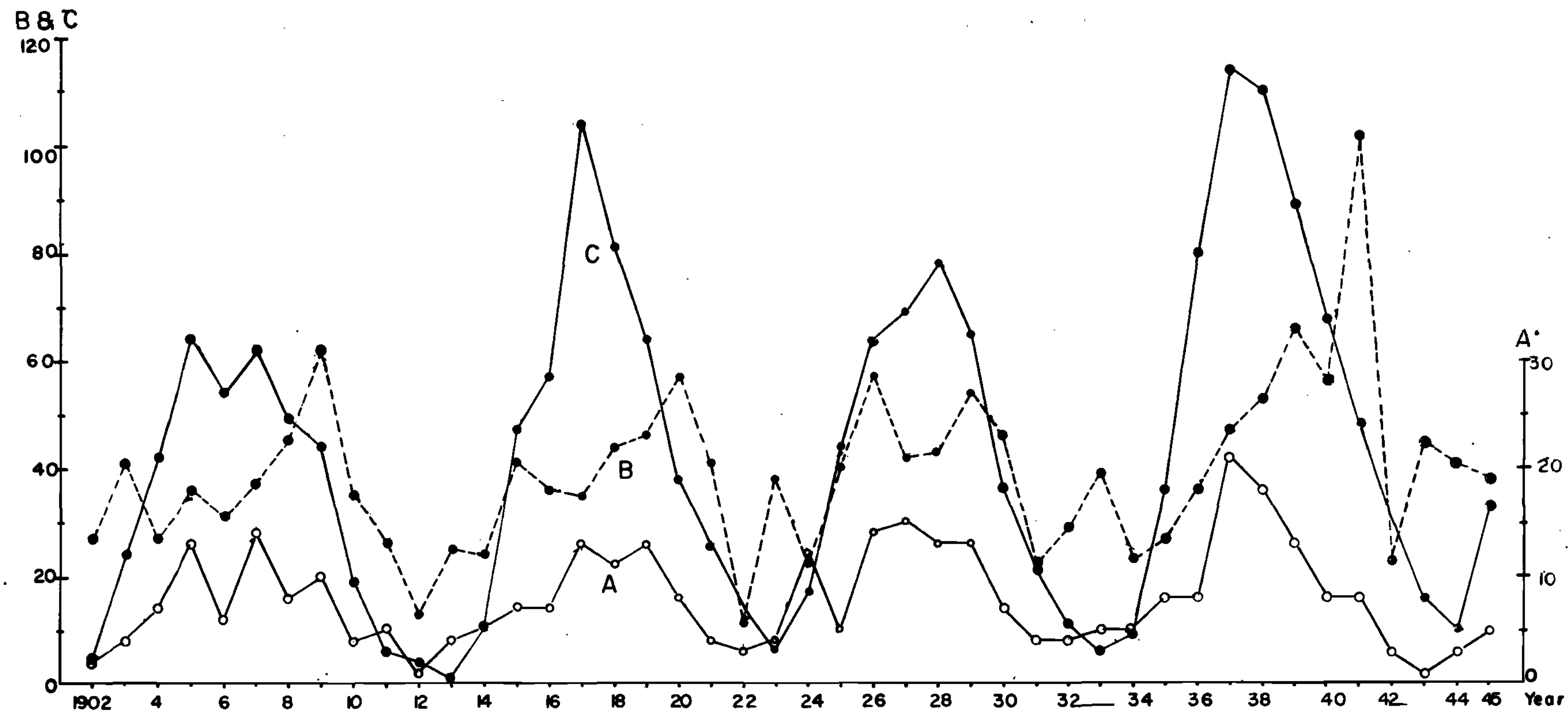

Fig. 3a. The number of SC storms (A), the annual mean class number (B), and the sunspot number (C).

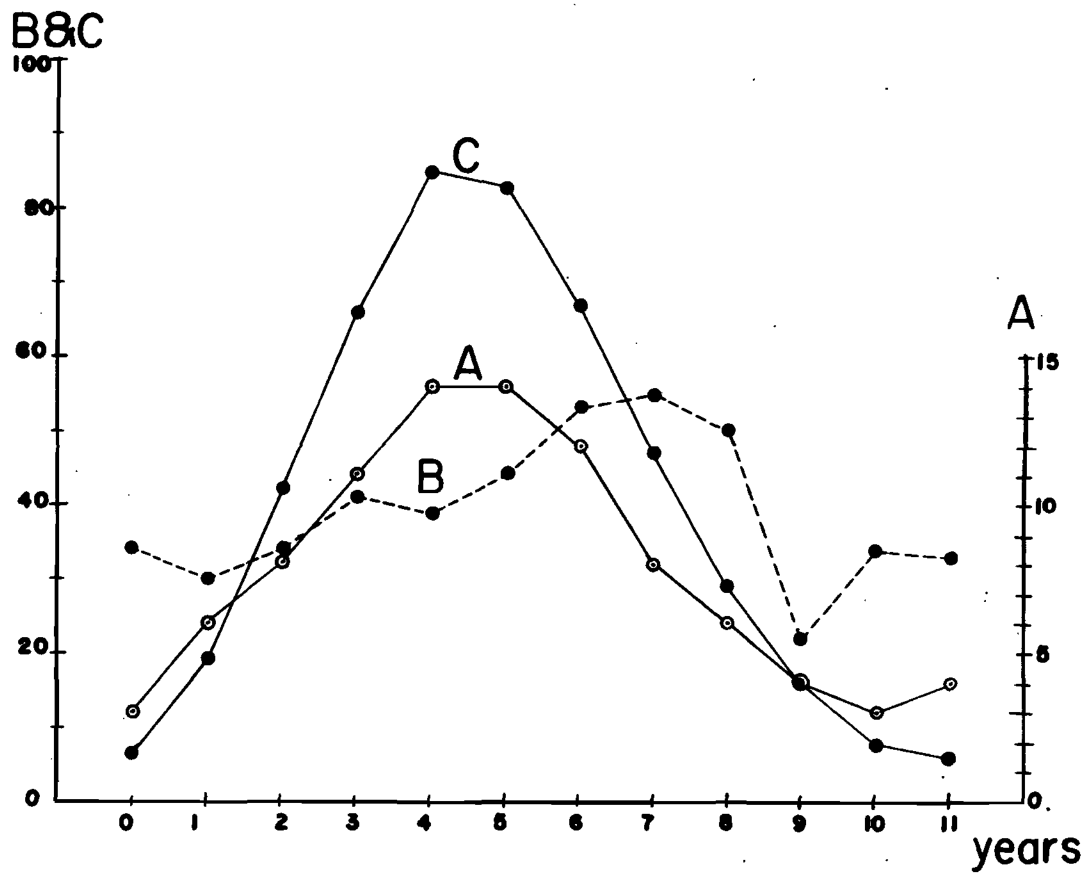

Fig. 3b. Changes of the number of SC storms (A) and the annual mean class number (B) with the sunspot number (C); averages over the four solar cycles.

fig 3b

of sudden commencement storms per year changes in parallel to the sunspot number; whereas the class number appears to attain its maximum a few years after sunspot maximum except for the cycle commencing in 1923. At any rate, the systematic parallelism with the solar cycle indicates on a statistical basis that the selection of magnetic storms made in the present study is not artificial and that the class number defined here is meaningful.

Reference may be made in this respect to earlier statistical studies on disturbances (not necessarily storms) compared with the annual mean sunspot numbers. C. Maurain(21) compared the number of days per year which were classed at Paris as disturbed, with the annual mean sunspot numbers. Eight hundred and fifty-five such days, or 57 per thousand, were selected in the forty-one years 1883-1923; their number per year varies between 50 (in 1883 and 1892) and 1 (in the sunspot minimum year 1913). An obvious correspondence can be seen between the sunspot numbers and the number of disturbed days. Correlations between annual means of magnetic and solar activity are discussed in Geomagnetism, p. 370. The correlation-coefficients between the annual mean values of the relative sunspot numbers and of the u-measures (see Section 3) are very high (0.869 for the years 1872 to 1930). In Figs. 7 and 8 shown in Geomagnetism, pp. 369, 370, a remarkable parallelism between them is clearly seen; the relation between the average intensity of disturbance and the sunspot number is much closer than between the variations in the number of disturbed days and the sunspot variations. In these earlier statistical diagrams the delay of maximum magnetic activity after sunspot maximum is not so clearly seen. The relationship between the daily sunspot numbers and the values of the magnetic activity on the same day is by no means so close as in the annual or monthly means; this was shown by Chree.[22]

W.M.H. Greaves and H.W. Newton[23][24] made a study on the relation between magnetic storms (1874 to 1925) and solar activity. Their study is to some extent an extension of an investigation on the same subject made by Maunder[25] with great magnetic storms (1875 to 1903) observed at Greenwich. In the first paper[23] they investigated to what extent individual storms bear a relation to individual spots, using 60 great storms whose ranges were equal to or greater than one degree in declination or 300 gammas in either H or V. The majority of these storms (54 out of 60) began with sudden commencements. A comparison between these great magnetic storms and large sunspots during the period studied showed that individual storms and individual spots are associated with each other more often than can be ascribed to mere chance. In the second paper[24] they added 343 storms to those already mentioned, by including all magnetic disturbances with ranges equal to or greater than 30' for declination or 150 gammas for H or V. All these storms, 403 in number, are listed in the volume of Greenwich Results for 1927, which has already been referred to in Section 2. They compared the total number of storms in each year during the period 1875 to 1927 with spot areas observed at Greenwich for the corresponding year. In forming the total numbers each "great" storm was counted as two. The two curves exhibit a general similarity; and in particular there is a close correspondence of the minima. But the parallelism there seen is not so good as in Fig. 3a of this paper. This is probably because sudden commencement storms are more closely correlated with sunspots than storms without this characteristic. Evidence supporting this view can be seen in the more recent study made by Newton[26].

Newton has made an extensive statistical study on sudden commencements with 681 cases (1879-1944) identified on the Greenwich magnetograms over six sunspot cycles. In his paper he examined the relationship between the annual numbers of sunspots and sudden commencements for the average of the six sunspot cycles. The curves shown there are remarkably similar to the curves in Fig. 3b in this paper. The ratio of the number of S.C.s at the sunspot minimum to that at the maximum found in Newton's curve is the same (within ±0.1) as the corresponding ratio determined from the curve A in Fig. 3b. In Newton's results, however, the annual number of S.C.s attains its maximum one year after the sunspot maximum, rather sharply diminishing on both sides of the maximum; whereas in Fig. 3b the number of S.C. storms for the year immediately after the sunspot maximum is the same as the corresponding number for the sunspot maximum. It is not certain whether this is a real difference, or an apparent one due to the difficulty, in superimposing several cycles, that sunspot cycles are not of equal length. In fact, in Fig. 3b the sunspot number does not decrease so rapidly after the maximum as in Newton's diagram.

Newton further discusses the same relationship between the annual sunspot number and (a) the annual number of small magnetic storms not associated with S.C.s; (b) the small magnetic storms with S.C.s. The data for (a) were obtained from the catalogue in the Greenwich Photoheliographic Results, 1927, (already referred to) with minor revisions, and brought up to 1944 by the annual summaries of magnetic storms given in The Observatory. The storms in the group (b) were selected from S.C.s. It was shown that the frequency distribution of (a) with respect to the 11-year sunspot cycle differs appreciably from that of (b). The annual number of the small storms with S.C.s (b) follows nearly the same course as that for S.C.s, as is anticipated.

In 1954, H.W. Newton and A.S. Milson[27] studied the statistical relationship between the distribution of great magnetic storms and the averaged sunspot curve, and also compared this distribution with those given by two categories of storms (a) with sudden commencement onset, and (b) with non-sudden commencement and indefinite onset. These three groups of storms were selected from the list in Greenwich Photoheliographic Results, 1927 and in annual additions to date in The Observatory. The lower limit for a great storm is 60' in declination or 300 gammas in the horizontal force or in the vertical force. with this limit 110 great storms were selected in the period 1878 to 1952. They compared the distribution of these storms with the mean sunspot number (Zurich) over the sunspot cycle (mean of seven cycles). Remarkable parallelism was found between these changes; the smoothed curve that would fit the points representing the annual numbers of great storms is virtually of the average sunspot curve. They also discussed the distribution (averaged for seven sunspot cycles) of the two groups of small storms: (a) S.C. and (b) non-S.C. Over the period considered there were 235 S.C. storms and 420 non-S.C. storms. It was shown that the S.C. storms follow the mean sunspot cycle given by sunspot numbers quite closely. The non-S.C. storms, however, have no pronounced peak at the sunspot maximum, but after two years from this epoch continue at a higher frequency level than the S.C. storms until the final drop towards the sunspot minimum.

Table 2. List of magnetic storms with sudden commencements, 1902 to 1945

Serial number	Year	Month	Date and Time of SC in GMT		Class number
1	1902	April	10	9.6	31
2		May	8	12.0	23
3	1903	April	5	23.4	57
4		August	25	22.9	24
5		December	13	12.5	46
6		December	30	3.2	37
7	1904	January	9	17.3	16
8		April	17	16.3	42
9		June	6	4.7	12
10		June	15	16.5	50
11		July	6	20.9	20
12		August	3	13.8	22
13		September	24	19.5	27
14	1905	January	3	23 7	24
15		January	5	9.9	21
16		January	16	23.9	6
17		February	3	1.7	41
18		March	2	13.3	43
19		March	7	3.0	45
20		April	1	1.2	44
21		June	5	1.9	12
22		July	5	21.6	30
23		August	2	0.5	52
24		November	12	8.1	47
25		November	15	15.3	72
26		December	12	2.9	31
27	1906	February	18	22.6	35
28		March	3	23.4	23
29		April	28	13.7	8
30		May	13	20.7	41
31		July	29	19.9	15
32		December	21	21.5	64
33	1907	January	11	8.8	41
34		January	14	19.6	13
35		February	7	8.1	50
36		February	9	14.2	66
37		March	10	5.0	32
38		March	11	17.3	18
39		March	21	13.4	24
40		May	18	14.0	36

Serial number	Year	Month	Date and Time of SC in GMT		Class number
41	1907	June	18	3.6	32
42		July	10	14.4	34
43		September	10	1.8	58
44		September	17	8.7	19
45		October	13	7.7	41
46		November	21	10.7	49
47	1908	February	22	12.2	26
48		August	8	7.7	32
49		August	19	0.2	19
50		August	21	8.6	12
51		September	11	7.9	84
52		September	28	9.2	97
53		November	17	1.0	50
54		December	4	8.8	42
55	1909	January	29	22.6	31
56		March	18	9.5	57
57		March	26	12.3	40
58		May	14	4.9	101
59		May	18	5.1	75
60		June	21	5.5	18
61		September	21	11.3	34
62		September	25	8.5	156
63		September	30	4.0	61
64		October	23	0.0	45
65	1910	February	20	10.2	8
66		March	27	23.3	60
67		September	29	8.0	20
68		October	19	7.2	50
69	1911	March	20	0.8	33
70		April	8	11.3	54
71		April	16	8.1	23
72		June	30	21.8	5
73		November	8	13.7	16
74	1912	September	17	14.0	13
75	1913	January	2	11.2	20
76		March	14	4.4	26
77		April	8	19.9	37
78		October	18	7.6	15
79	1914	January	4	20.0	8
80		April	6	8.1	43

Serial number	Year	Month	Date and Time of SC in GMT		Class number
81	1914	June	25	2.0	8
82		July	5	1.4	32
83		November	26	17.7	27
84	1915	January	4	3.5	5
85		March	6	15.4	13
86		April	7	19.7	22
87		April	26	4.0	17
88		June	16	13.0	138
89		October	23	12.8	14
90		November	5	14.6	78
91	1916	January	11	4.0	38
92		February	12	16.5	6
93		March	8	0.6	36
94		May	20	23.0	36
95		June	29	20.4	31
96		August	22	18.5	28
97		August	26	19.7	80
98	1917	January	4	5.0	96
99		February	14	5.0	35
100		April	25	14.4	16
101		May	16	5.7	12
102		May	25	9.1	15
103		June	9	0.1	2
104		June	24	13.7	14
105		July	2	3.7	10
106		August	9	4.2	75
107		August	20	8.4	58
108		September	5	6.2	39
109		December	7	10.3	10
110		December	16	9.2	69
111	1918	January	12	4.0	14
112		January	28	14.8	29
113		February	5	6.8	28
114		March	7	21.2	80
115		April	10	20.9	46
116		April	29	21.3	48
117		June	9	23.1	68
118		August	15	15.8	46
119		September	21	4.3	24
120		November	29	13.3	40

Serial number	Year	Month	Date and Time of SC in GMT		Class number
121	1918	December	25	3.8	59
122	1919	January	3	18.2	60
123		January	12	23.4	21
124		January	31	10.7	15
125		February	27	19.4	27
126		April	6	7.8	26
127		May	1	22.9	62
128		August	11	7.0	97
129		September	2	12.4	46
130		September	23	20.5	51
131		October	1	16.2	77
132		October	8	21.5	22
133		October	22	3.1	49
134		October	26	14.6	47
135	1920	March	4	11.6	97
136		March	13	12.9	14
137		March	22	9.2	193
138		May	13	0.3	47
139		September	22	2.3	19
140		November	26	12.9	32
141		December	4	5.0	2
142		December	25	10.1	55
143	1921	April	18	14.5	17
144		April	28	19.5	39
145		May	19	20.1	76
146		June	3	10.7	32
147	1922	January	30	23.5	32
148		March	14	7.1	1
149		December	9	21.9	0
150	1923	January	20	3.0	9
151		March	24	9.9	56
152		June	12	20.5	32
153		September	26	4.0	53
154	1924	January	29	5.4	51
155		March	29	3.6	16
156		April	6	8.2	8
157		April	24	21.6	15
158		May	21	6.0	52
159		June	9	14.2	57
160		June	18	7.0	18

Serial number	Year	Month	Date and Time of SC in GMT		Class number
161	1924	July	9	5.4	3
162		July	20	16.6	8
163		August	4	1.1	8
164		September	4	5.7	17
165		December	11	22.9	6
166	1925	May	3	22.4	53
167		August	22	14.8	17
168		September	1	17.8	25
169		September	21	2.3	45
170		December	27	14.8	58
171	1926	January	3	22.4	0
172		January	22	15.6	46
173		January	26	16.3	107
174		February	10	5.8	30
175		February	23	16.4	97
176		March	5	10.1	44
177		March	17	21.1	21
178		April	14	14.1	134
179		April	21	10.3	28
180		May	3	21.2	48
181		June	1	11.2	68
182		September	14	8.8	50
183		October	13	19.4	81
184		October	24	6.4	38
185	1927	January	4	20.1	10
186		January	7	10.4	43
187		January	24	23.7	34
188		February	9	16.9	30
189		March	27	14.5	12
190		April	13	23.8	61
191		May	27	4.5	17
192		July	21	21.0	62
193		August	20	6.6	73
194		August	29	0.0	53
195		October	10	8.4	23
196		October	12	10.4	56
197		October	22	6.7	77
198		November	18	4.6	38
199		December	12	19.7	34
200	1928	February	12	7.3	12

Serial number	Year	Month	Date and Time of SC in GMT		Class number
201	1928	May	5	2.8	12
202		May	10	12.2	39
203		May	27	14.8	88
204		July	2	8.5	13
205		July	7	23.5	105
206		August	4	17.1	30
207		August	25	22.6	47
208		September	7	13.8	65
209		September	24	16.4	22
210		October	18	7.4	68
211		October	24	17.8	36
212		November	11	17.0	17
213	1929	January	3	7.1	31
214		February	16	23.1	87
215		February	26	19.4	86
216		March	11	13.9	116
217		March	15	8.5	71
218		July	5	9.1	15
219		July	10	11.6	26
220		July	14	16.5	39
221		July	31	21.1	45
222		August	14	12.5	34
223		September	6	23.6	31
224		October	16	11.2	40
225		December	3	12.1	82
226	1930	January	3	8.1	22
227		May	4	23 9	46
228		June	15	10.5	28
229		July	9	14.9	27
230		September	18	8.8	68
231		November	13	19.5	45
232		December	3	1.1	88
233	1931	February	13	9.0	16
234		June	1	15.5	37
235		June	26	15.0	17
236		July	23	3.4	17
237	1932	February	2	20.3	16
238		April	22	5.5	13
239		October	14	17.8	41
240		December	14	12.7	45

Serial number	Year	Month	Date and Time of SC in GMT		Class number
241	1933	February	19	10.0	39
242		April	30	16.5	56
243		May	29	6.5	14
244		July	23	9.7	26
245		September	8	21.4	61
246	1934	January	1	8.2	33
247		February	8	17.3	31
248		July	3	10.5	9
249		July	30	3.3	35
250		December	1	4.9	5
251	1935	January	27	14.8	21
252		May	1	12.8	36
253		July	7	21.1	31
254		August	19	5.4	17
255		September	23	1.6	51
256		October	24	6.7	38
257		November	29	3.9	8
258		December	24	19.6	15
259	1936	February	2	15.1	10
260		May	10	8.1	21
261		June	18	9.7	67
262		July	2	4.8	44
263		July	5	2.5	6
264		November	2	14.3	8
265		November	28	23.6	61
266		December	27	3.5	72
267	1937	January	27	8.6	50
268		February	2	23.1	60
269		February	18	19.1	1
270		March	26	20.9	36
271		March	31	3.3	59
272		April	24	12.0	72
273		April	25	15.8	38
274		April	26	17.9	48
275		April	27	19.0	47
276		May	4	16.9	62
277		June	4	14.4	63
278		June	13	8.7	6
279		June	27	2.8	7
280		July	19	12.9	34

Serial number	Year	Month	Date and Time of SC in GMT		Class number
281	1937	August	1	21.8	74
282		August	22	3.1	78
283		September	10	17.9	45
284		September	30	13.8	62
285		October	3	11.3	58
286		October	7	5.3	82
287		October	9	6.6	5
288	1938	January	16	22.6	108
289		January	25	11.9	154
290		February	6	3.2	31
291		February	8	11.0	25
292		March	21	22.7	67
293		April	13	11.7	25
294		April	16	5.8	66
295		May	11	15.9	115
296		June	7	22.1	11
297		June	12	17.9	4
298		July	4	12.1	28
299		July	30	4.6	53
300		August	3	21.6	22
301		August	10	3.4	37
302		September	13	18.6	64
303		September	27	22.0	20
304		September	30	10.4	16
305		October	7	6.2	100
306	1939	February	5	19.8	59
307		February	24	17.1	126
308		March	27	17.6	60
309		April	17	1.9	91
310		April	24	17.6	15
311		May	5	20.7	56
312		June	14	0.1	57
313		July	4	14.1	60
314		July	21	10.0	3
315		August	12	1.7	72
316		August	22	0.7	126
317		September	2	21.7	25
318		October	13	2.1	112
319	1940	January	3	14.7	30
320		March	29	16.1	129

Serial number	Year	Month	Date and Time of SC in GMT		Class number
321	1940	April	25	2.1	54
322		May	23	17.9	17
323		June	25	2.9	54
324		July	13	8.0	34
325		September	26	17.1	47
326		November	12	7.1	79
327	1941	March	1	3.9	187
328		April	24	7.3	50
329		June	13	3.7	24
330		July	4	3.7	184
331		August	4	1.5	37
332		September	18	4.2	179
333		October	31	3.7	87
334		December	1	6.0	67
335	1942	March	1	7.5	36
336		March	5	4.3	16
337		July	10	23.6	18
338	1943	March	29	18.6	45
339	1944	March	26	2.0	29
340		April	1	23.4	47
341		December	15	18.9	46
342	1945	March	27	20.6	10
343		April	1	5.0	34
344		April	11	7.5	39
345		October	23	23.7	26
346		December	13	12.7	82

5. Method of analysis here used.

In the present analysis of magnetic records, hour-to-hour differences of all quantities concerned were used instead of absolute or relative values as given in the publications. This method was adopted to avoid (a) dealing with large numbers such as are given in observatory records, and (b) complications arising from missing entries in forming means of sets of values reckoned from different levels. In this respect a further detailed discussion is given in Section 9(B). These hour-to-hour differences were converted into absolute values measured from some appropriate level at a convenient step in each analysis, as will be described later. In the case where there are no missing or incomplete data, the method based on such hour-to-hour difference basis should give exactly the same results as would be obtained by the ordinary method.

In paper 1 magnetic hourly records for the first 48 hours after the storm commencement were used. In this paper the 4 pre-storm hours and the first 72 hours after the storm commencement were included in the analysis. In what follows storm-time is assigned to the hourly values in such a way that the value for the time closest to the sudden commencement corresponds to the origin of storm-time. Or, more precisely, (a) when instantaneous values are given, the full hour closest to the commencement is taken to be 0^h of storm-time; (b) when mean values averaged over 60 minute intervals centered at full hours are given, they are considered to represent values at full hours, so that storm-time is assigned in the same way as in the case of (a); and (c) when mean values are given for 60 minute intervals commencing (and ending) at full hours, they are assigned to the center of these intervals, and the one that stands closest to the sudden commencement is taken to refer to 0^h of storm-time. On the average, therefore, if magnetic storms are distributed uniformly with respect to time, the origin of the storm-time can be considered to coincide with the time of sudden commencement. To the four hours prior to the origin so defined are assigned the storm-times -1^h, -2^h, -3^h, and -4^h, successively backwards, and to the 72 hours after 0^h were assigned the successive storm-times 1^h, 2^h, ..., 71^h.

The method of analysis is described below; it applies to each element and each observatory for each seasonal subgroup. The illustration of the following treatment will be given in Appendix.

(A) For a set of magnetic storms (weak storms in this paper) in a certain season, hour-to-hour differences for the 76-hour period were taken from the published (or manuscript) data of hourly values, starting from the level at storm-time -1^h. For the pre-storm hours, hour-to-hour differences were taken backwards from the level at -1^h. These hour-to-hour differences were entered in Table A, which contains 76 columns referring to storm-times -4^h to 71^h, and the same number of rows as that of storms in the subgroup. The hour-to-hour differences under -1^h are necessarily all zeros. There may be blank or incomplete rows when the data were lacking or incomplete.

(B) Table B, containing 24 columns and the same number of rows as in Table A, was formed for the solar daily variation on quiet days (denoted by Sq). In each row were entered, according to storm-time for each storm, a series of hour-to-hour differences of the hourly means of five international quiet days for the month in which the storm occurred. When a storm continued from one month to the next, the mean of the two months was used in Table B. When the monthly means of five international quiet days were not available, means of local quiet days or means of all days were substituted for them. In order to allow for non-cyclic variation, Sq uncorrected for non-cyclic variation was used whenever available. The reason why allowance was made of the non-cyclic variation will be given at the end of this Section.

(C) From each value in Table A for the first 24 hours, the value in the corresponding entry in Table B was subtracted. The remainder was entered in Table C in the corresponding entry. Entries under -1^h in Table C are all zeros, as in Table A, because Sq is also reckoned from this level. For the rest of the pre-storm hours, Sq was measured backwards from the level at -1^h and was subtracted from the corresponding entries in Table A. This was done because in Table A, hour-to-hour differences for the pre-storm hours were given as reckoned backwards from the level at -1^h. Table C so formed, therefore, gives the whole disturbance variation on an hour-to-hour difference basis.

The mean was taken for each column; the series of these means gives the storm-time variation on an hour-to-hour difference basis. This can be converted into values relative to the level at -1^h by consecutively adding the hour-to-hour differences.

(D) Table D was formed for each 6-hour interval in the first and second days, and for each 8-hour interval in the third day, each table containing 24 columns corresponding to 0^h to 23^h of local-time and to the same number of rows as in Tables A, B, and C. For each interval, values in each row in Table C, six or eight in number, were transcribed onto Table D in the same row as in Table C, and in columns of corresponding local-times. Thus, from each Table C eleven

Tables D were made. For the first 6-hour interval for H, the mean storm-time variation on an hour-to-hour difference basis, as obtained in (C), was subtracted from the entities in Table C before they were transcribed into Table D. This reduction was made because during the first six hours the storm-time variation in H changes sign. During the second six hours, however, the change in H is nearly linear, though rapid (see Figs. 4a and 4b). Therefore, the mean Dst, is removed better by subtracting the mean of all values in Table D for this interval, rather than by subtracting the mean Dst for each storm-time. For the third and later intervals for H the change (on an hour-to-hour difference basis) is very small and is subject to fluctuations, so that the same method as for the second 6-hour interval was applied to remove Dst. This holds also for V and D for all intervals, because their Dst is very small. In practice, this was done in the following way. Columnar means are taken in each Table D. The sum of the columnar means is nearly zero for the first 6-hour interval for H, because the mean Dst has already been subtracted. Sums of those for other intervals for H, and for all intervals for V and D, are in general not zero. The zero level of these columnar means was adjusted so that the sum becomes null. This amounts to subtracting the mean Dst averaged over the interval. The series of values so obtained, 24 in number, represent the disturbance local-time inequality, for the interval, on an hour-to-hour difference basis. Then DS on the ordinary basis is readily obtained by successively adding these hour-to-hour differences from an arbitrary level, and by adjusting the zero level so that the sum of DS over 24 hours becomes zero.

In forming Tables C (Sq-tables), Sq uncorrected for the non-cyclic variation was used whenever available. A brief account will be given why the non-cyclic variation was taken into account. W. van Bemmelen(28) made an investigation on the after-disturbance effect. He studied the changes, from day to day, in the daily means of the three magnetic elements at many observatories, during many days following upon a number of magnetic storms. Immediately after a storm the daily mean in H is generally below its mean level, but it increases gradually during the following days. McNish(29) discussed the non-cyclic variation in the horizontal force at Watheroo for the years 1919 and 1925-29; he plotted the daily mean values of H at Watheroo for days selected by the Department of Terrestrial Magnetism and the U.S. Coast and Geodetic Survey as being very quiet, and which immediately preceded or succeeded internationally selected quiet days. Each mean was assigned a number representing the interval of time elapsing since the last internationally selected disturbed day. From such data he determined the average increase in H after a magnetic disturbance as a function of time. The trend of the recovery in H was found to be substantially linear at least to 10 days after the last disturbed day; the slope of the recovery is about 4 gammas per day.

It is probably reasonable to assume that such trend of recovery from a previous storm exists not only during quiet days, but also during the magnetic storms that follow. As we have seen in the study made by Chapman, the storm-time variation in H is characterized by a recovery after the maximum diminution is reached. If the above assumption is correct, the recovery found in H there is made up of two parts: one is recovery from the preceding storms and the other that from the storm under consideration; even during the initial phase during which H rises above the pre-storm level, or during the phase where H decreases rapidly, this recovery probably exists. Therefore in order to study the pure effect of a storm, the non-cyclic variation should be removed from the storm data as actually observed. It is not certain, however, whether during a magnetic storm, the part of the non-cyclic variation that is ascribed to recovery from the preceding storm is the same as the non-cyclic variation that would be observed, if the magnetic storms had not occurred. In the present work it was assumed that throughout magnetic storms the non-cyclic variation preserves its typical form as observed during adjacent quiet days. Then the simplest way to remove the non-cyclic variation is to subtract Sq uncorrected for the non-cyclic variation. Some more remarks will be made on the non-cyclic variation in Section 9(E).

6. The storm-time variation Dst.

By the method described in (C) the storm-time variations for the horizontal force H, east declination E (in force unit), and the vertical force V were formed for each observatory for each season. Diagrams for these individual cases are not shown in this paper. In order to eliminate irregularities, the results were averaged for groups of observatories chosen according to their geomagnetic latitude, as shown in Table 4. In the last column in Table 4 is given the mean geomagnetic

Table 4. The grouping of observatories according to their geomagnetic latitude.

Group No.	Number	Observatories	Mean gm latitude
1	1	Godhavn	80° N
2	3	Tromsö, Sodankylä, Lerwick	65° N
3	4	Sitka, Eskdalemuir, Lovö, Rude Skov	59° N
4	4	DeBilt, Greenwich, Val Joyeux, Cheltenham	52° N
5	2	Ebro, Tucson	42° N
6	2	Porto Rico, Kakioka	28° N
7	2	Honolulu, Zikawei	21° N
8	7	Rio de Janeiro, Apia, Batavia, Cape Town, Watheroo, Toolangi, Christchurch	28° S*

* Weighted Mean

latitude for each group. The groups will be referred to hereafter by the group number indicated in the first column in Table 4. For group 8, which consists of all observatories in the southern hemisphere, the mean of the latitudes weighted by the amount of data contributing to the group was taken, instead of the numerical mean of their latitudes. For groups 2 to 7, the weighted mean latitude does not differ significantly from the simple mean, therefore, the latter is given in Table 4.

The mean Dst for these groups of observatories was obtained for each season separately, and then averaged over the three seasons. The Dst variation so obtained is still subject to small irregularities. In order to remove such irregularities, averages were further taken over half-day intervals after the first 12 hours. For Godhavn and group 2 (Tromsö, Sodankylä, Lerwick) a large fraction of DS and of the irregular fluctuations remained even after such averages were taken. Hence Dst was further averaged over each of the first, second, and third days.

The storm-time variation so obtained for declination showed systematic changes during the five half-day intervals after the first 12 hours at all latitudes except at Godhavn. These changes are all within a few gammas in groups 3 to 8. For group 2, the change in east declination reached 10 gammas in the second day, and was slightly smaller in the first and third days than in the second. These systematic changes in Dst for declination are thought to be due to the fact that the actual Dst field is nearly in the geomagnetic meridian, and that the horizontal force at each observatory is, in general, not exactly in the meridian. In order to test if this view is correct, the average deviation, χ, of the horizontal force from the geomagnetic north was computed for each group (2 to 8). If the Dst field is in the geomagnetic meridian, and if χ is not zero, the Dst field will have a component in the direction perpendicular to that of the horizontal force. This component is expressed by H tan χ, where H is the observed change in the horizontal force. The observed change in declination must contain this component, if the assumption is correct. The change in E computed by H tan χ was in fact in the same direction and of the same size as the Dst variation for E that was originally obtained. The computed change in E was subtracted from the uncorrected Dst; the residual change will be called the storm-time variation in E. The variation so defined, therefore, is the deviation of the observed field from the geomagnetic meridian (measured in the unit of force). For the horizontal force the component of the Dst field along the geomagnetic meridian was likewise calculated for groups 2 to 8. This component will now be called the storm-time variation in the horizontal force. In fact, however, the difference between this component and the Dst for H originally obtained was negligible for the groups 3 to 8, and was only about 1 gamma for the group 2. At Godhavn the Dst for E does not show a systematic change. Therefore, no correction was made on the Dst. The results are shown in Figs. 4a and 4b. In Figs. 4a and 4b are drawn the average storm-time variations (of weak magnetic storms) for the three magnetic elements for the groups 1 to 8. The observatories contributing to each group, and their mean geomagnetic latitude, are shown in the figures. The variations are drawn on different scales, as indicated in the figures.

The general features of the storm-time variation will now be described. At all latitudes up to about 60°, Dst (H) rises abruptly at the storm commencement, reaching its maximum at 1^{h} in storm-time. (Times mentioned in this Section are all storm-times. They are exact times on a statistical basis, reckoned from the storm commencement. See Section 5.) The maximum H is 14 gammas at latitude 21° (group 7), and 11 gammas in each of the groups 4, 5, 6, that is, up to latitude 52°. After the maximum is reached H decreases rapidly and almost linearly, to 8^{h} (or a little later) at all these latitudes, the rate of decrease

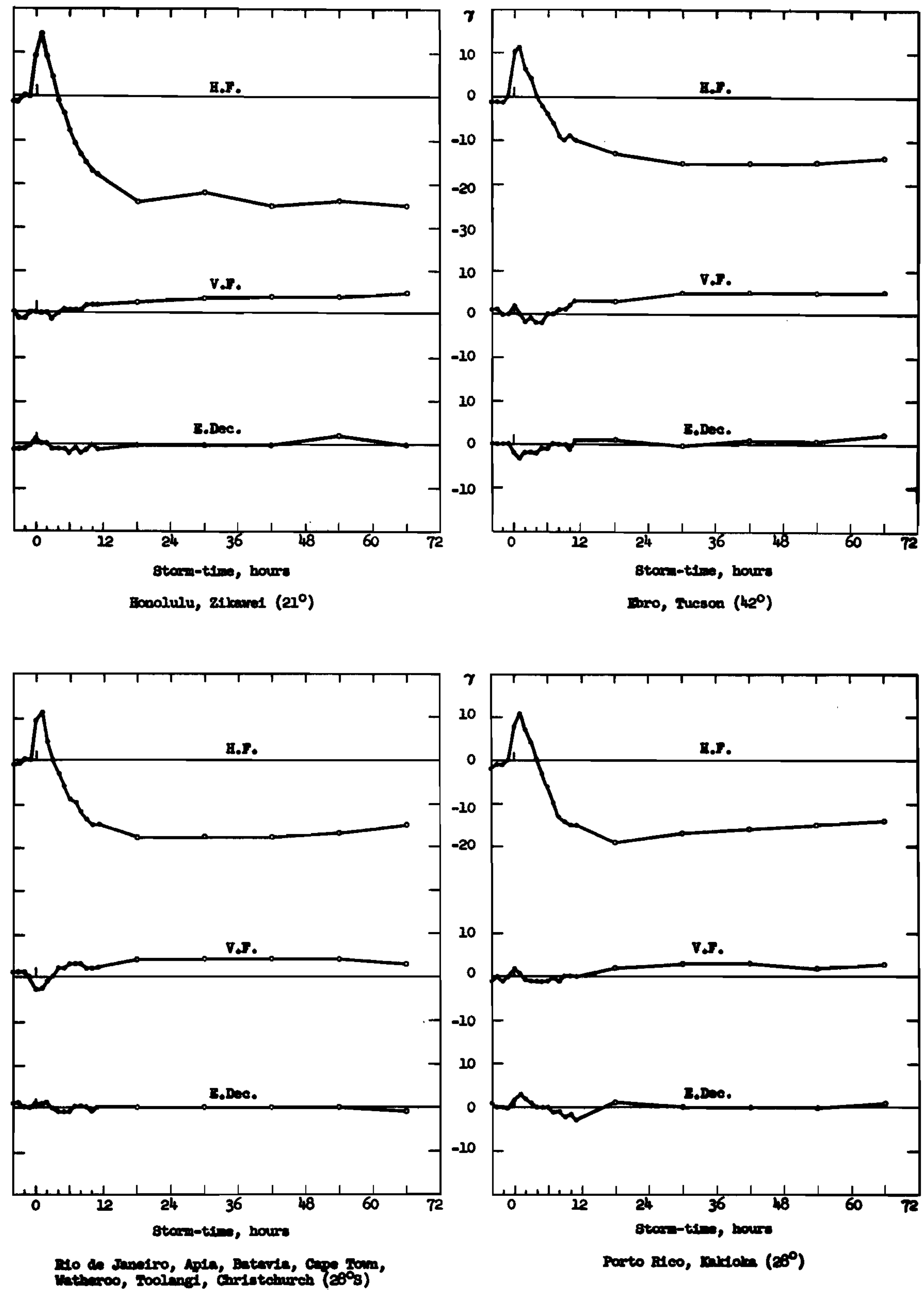

Fig. 4a. Averaged storm-time variations of weak magnetic storms in different geomagnetic latitudes.

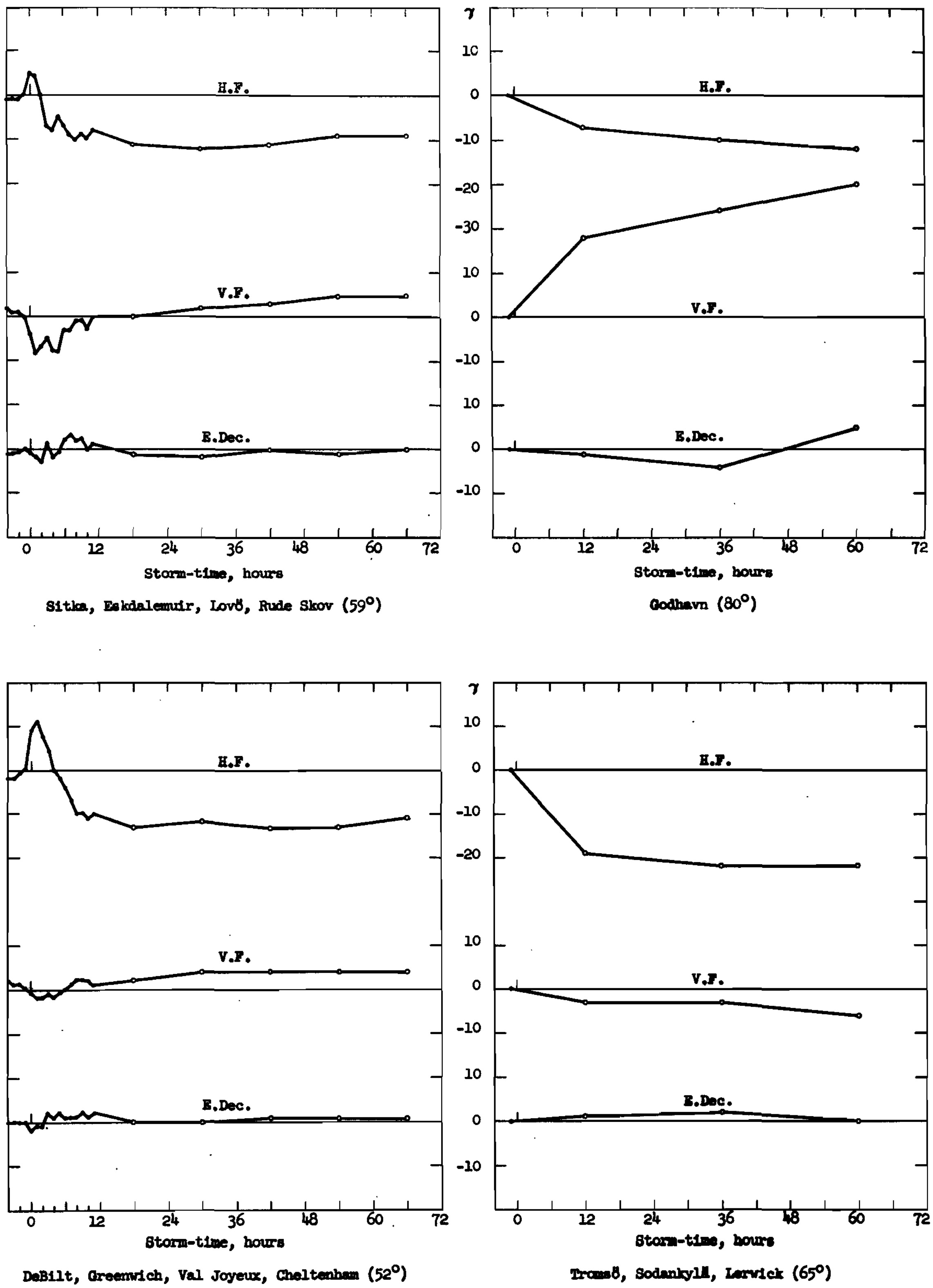

Fig. 4b. Averaged storm-time variations of weak magnetic storms in different geomagnetic latitudes.

then diminishing slowly at latitude 21°, and faster at higher latitudes. At latitude 21° (group 7) minimum H is attained in the latter half of the second day; this level is maintained through the third day with fluctuations superimposed on it. At higher latitudes (groups 4, 5, 6) up to latitude 52°, minimum H is reached in the second half of the first day or in the first half of the second day. This level is maintained through the second day, and is followed by a very slow recovery, the amount of recovery at the end of the third day being only of the order of a few gammas.

At latitude 59° the rise in H in the initial phase is still found, though there it is much smaller than in lower latitudes. Maximum H appears to be reached at or shortly after the storm commencement. The rate of decrease after the maximum is much greater than in lower latitudes. At latitudes 21°, 28°, 42°, and 52°, H crosses the pre-storm level at 4^h; whereas at latitude 59°, it does so at about 2^h. At this last latitude the rate of decrease rapidly diminishes at 3^h or 4^h; thereafter large fluctuations are superimposed on Dst. Minimum H seems to be reached in the first half of the second day, after which a slow recovery follows, the rate of recovery being about the same as in the latitudes of groups 4, 5, 6. At latitude 65° (in the auroral zone) Dst(H) is, on the average, about twice as large as that at 59°. On account of the large irregular magnetic variations in the auroral zone, it is not possible to say whether or not Dst(H) there suffers any reversal during the initial phase. At latitude 80° (within the auroral zone) Dst(H) is reduced to about a half of that in the zone.

By comparing Dst(H) for the southern stations (mean latitude 28° S) with that at 28° N, it can be seen that the storm-time variation in H is approximately symmetrical with respect to the geomagnetic equator; the differences between them are probably fortuitous.

Dst(E) is very small at all latitudes. Whether there is any systematic change in Dst(E) can hardly be concluded without further careful investigation. It is also uncertain whether or not the relatively large change in E for Godhavn is fortuitous.

Dst(V) is opposite in sign to that for H, and much smaller in magnitude. In the southern hemisphere, Dst for Z, reckoned positive downwards, is opposite to Dst drawn in Fig. 4a. Hence Dst(Z) is antisymmetrical with respect to the equator. The most important feature in Dst(Z) is that on passing the auroral zone it changes sign. Dst(Z) for the group 2 is of the order of a few gammas and is negative, or upward, whereas at Godhavn (80°) its sign is reversed and it reaches 20 to 30 gammas. This can be considered as the effect of the concentrated westward electric current flowing along the auroral zone. The negative change observed for the group 2 is probably due to the fact that Sodankylä and Lerwick are located slightly to the south of the zone. It will be interesting to determine Dst(Z) for the three stations in this group separately, to see if Dst(Z) increases in magnitude from Lerwick to Sodankylä and then decreases to Tromsö.

In concluding the description of the storm-time variation a remark should be made on the sudden impulse at the outbreak of a storm. A typical S.C. storm commences with sudden impulses in the three magnetic elements. The most notable of these impulses is that in H. The sudden impulse in H is in general a rapid rise in a duration of the order of several minutes. This rapid change cannot of course be investigated by means of hourly values. In order to study more closely the characteristics of the changes in the three elements in the first hour or two, values of H scaled at intervals much shorter than hourly intervals must be used.

7. The disturbance local-time inequality DS.

The disturbance local-time inequality, DS, which was obtained by the method described in (D) in Section 5, was combined for the groups of observatories as was done for the storm-time variation. In order to find the average characteristics of DS in each of the first, second, and third days at various latitudes, the four quarter-day sets of DS for each of the first and second days, and the three 8-hour sets for the third day, were further combined. The results for H, E, and V are shown graphically in Figs. 5, 6, and 7. In the figures Sq and the average DS for the first, second and third days are given in columns denoted by a, b, c and d, respectively. Grouped observatories are arranged in decreasing order of latitudes, from 1 to 8. Their latitudes are indicated in parentheses. In Figs. 5, 6, and 7 Sq is represented for all groups 1 to 8 on the same scale, in contrast to the use of different scales for different groups, for Dst and DS. The force scales for DS (H, E and V) for the groups 1 and 2 are forty-fold and twenty-fold, respectively, those for groups 3 to 8. DS(V) is much less than DS(H) and DS(E) for group 1; hence it is also shown on a larger (eight-fold) force scale by a broken line. DS(E) and DS(V) for the group 2 are enlarged with broken lines on a two-fold force scale. The rest of the DS curves are drawn on the same scale as for Sq.

It is clear from Figs. 5, 6 and 7 that the DS variations are quite different in type from the Sq variations in all three elements. Characteristics of DS for H, E and V will be described below.

DS(H) preserves the same phase from group 8 (28° S) to group 4 (52°). There is a reversal in phase between group 4 (52°) and group 3 (59°), probably at about 55°, or below. A transitional character is evident

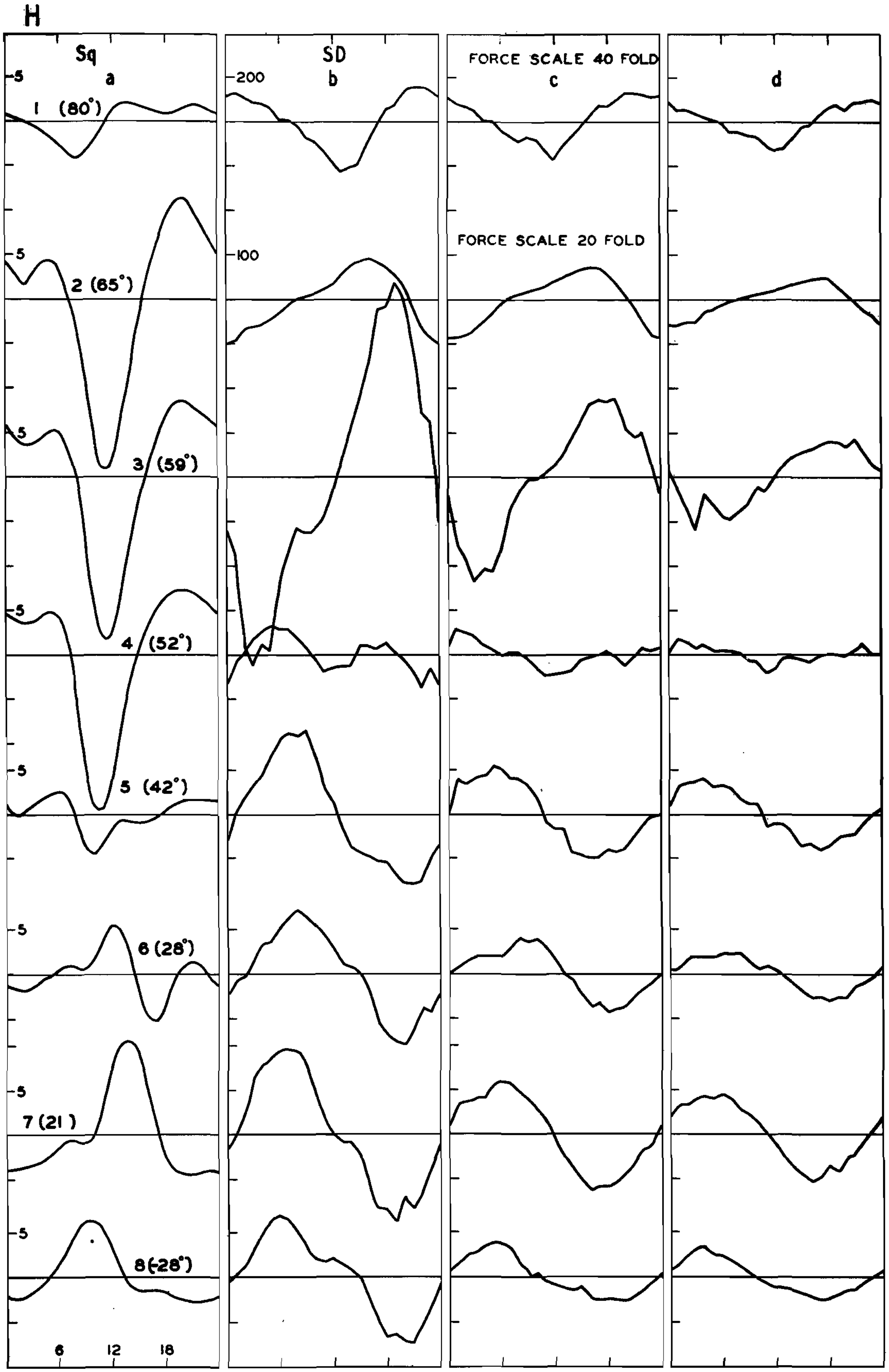

Fig. 5. Sq and DS for the horizontal force.

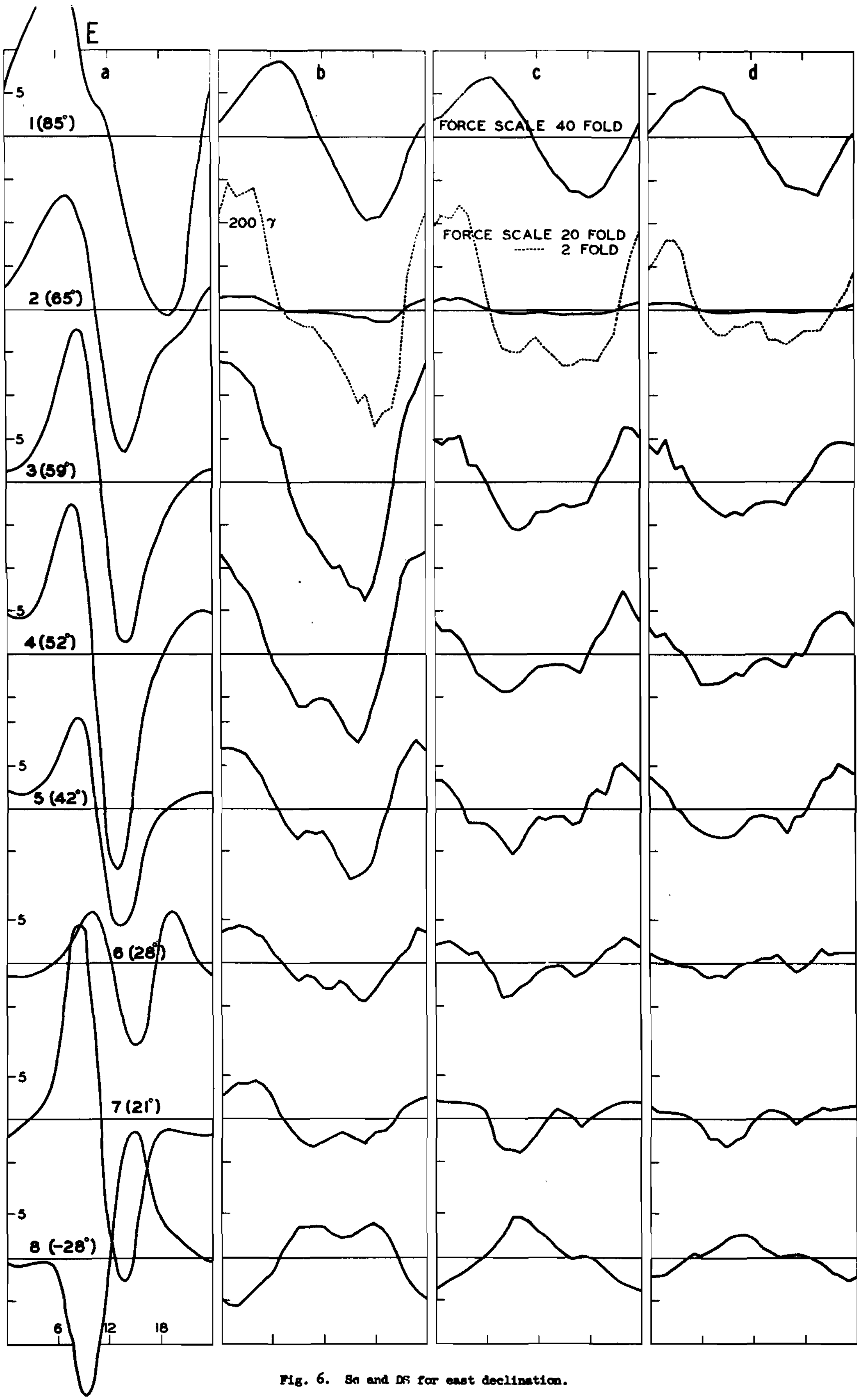

Fig. 6. Sq and DS for east declination.

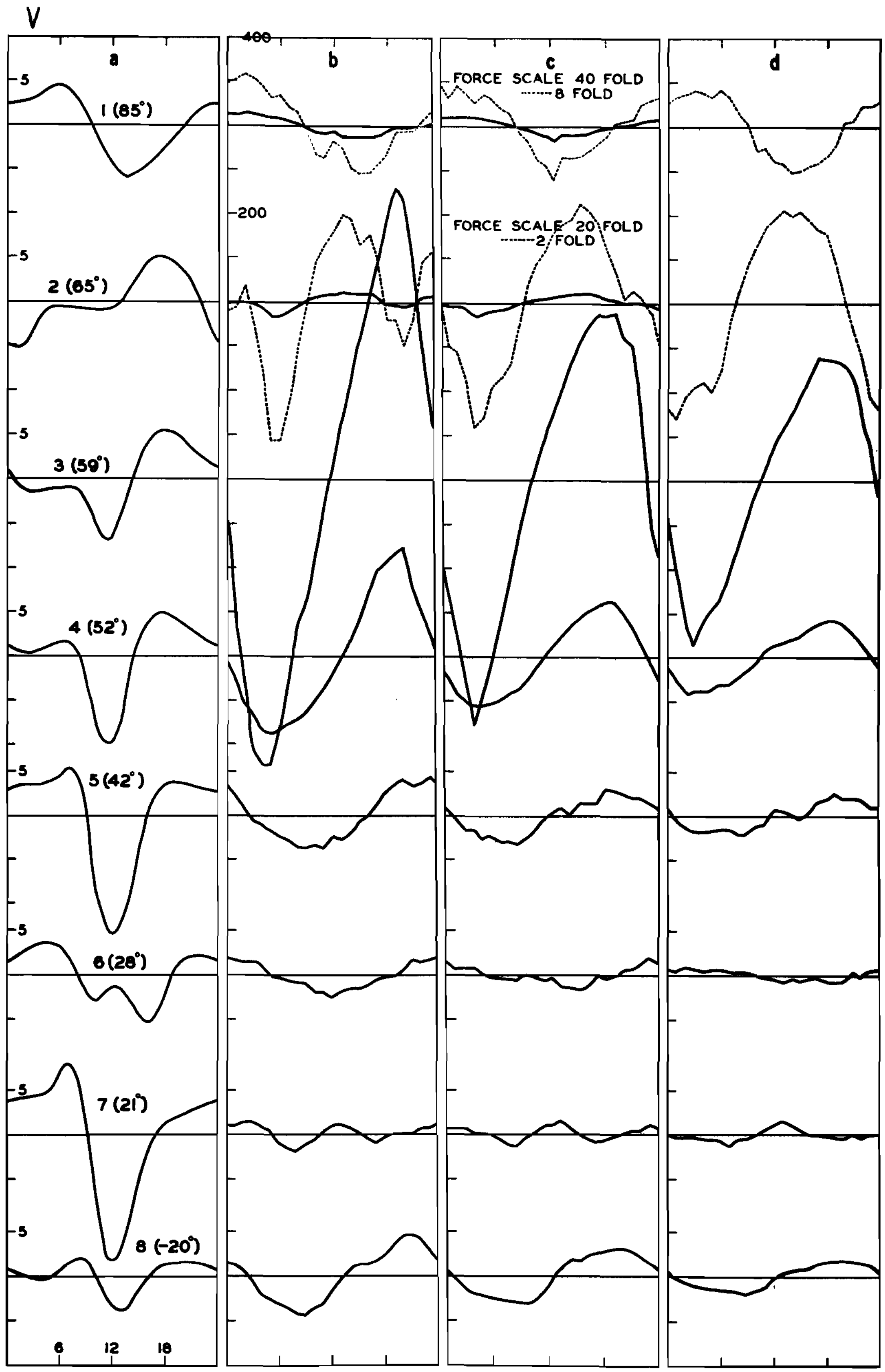

Fig. 7. Sq and DS for the vertical force.

in group 4 (52°); the range there is considerably smaller than at latitudes 42° and 59°. It will be worth while examining whether any of the four observatories (De Bilt, Greenwich, Val Joyeux, Cheltenham) in the group 4 shows a clearer transitional nature. It may also be possible to subdivide magnetic storms so that the two different types of DS(H) could be shown separately at this latitude. In a future study these problems will be discussed in more detail. The range increases rather rapidly from group 4 to group 3, and increases still more from group 3 to group 2 (65°), preserving nearly the same pattern. On crossing to within the auroral zone, the range increases even more, reaching 400 gammas at latitude 80°. At the same time a great change of type is seen.

In DS(E) the phase is reversed on crossing the equator; otherwise no reversal in phase is observed up to latitude 80°. The range in DS increases steadily with latitude to 65°, where it reaches about 60 gammas, and then rises greatly from latitude 65° to latitude 80°, where it is about 750 gammas.

The phase in DS(V) - not DS(Z) - for groups 3, 4 and 8 are typical of the phase in the ordinary SD. In groups 5 and 6, the phase is shifted from the normal by 4 to 6 hours. In group 7 (21°) the variation is of a different type and is rather irregular. The range is very small at this latitude, and increases gradually with latitude to the latitude for group 3 (59°). From group 3 to group 2 (65°) there is a moderate decrease in the range of DS(V) which is reversed in crossing under the auroral zone. At latitude 80° the range in V is about 100 gammas, which is much smaller than in H (nearly 400 gammas) and E (nearly 800 gammas). The most important feature in V is that the phase is reversed in crossing the auroral zone. If Z is taken instead of V, it also suffers a reversal in crossing the equator.

DS(V) at latitude 28° S is of the same type as that at 42° N; but it is not the same as DS(V) at latitude 28° N. DS(V) at latitude 21° N is very small and irregular, suggesting a possibility that the latitude with respect to which DS(V) is symmetrical (or, where DS(Z) is reversed) is near 21°, rather than the equator. This question will be studied in the near future with additional storm records from Bombay. It seems also necessary to subdivide the group of the southern observatories to examine the change of DS with (southern) latitude, if such subdivision will not introduce serious uncertainties due to irregular variations that are not averaged out.

In all three components the Sq variations in the polar region are negligible compared with the DS variations, and Sq(V) for groups 1 and 2 is not pure, being evidently affected by some admixture of DS(V). These results are in agreement with the results obtained by Chree[11] in reference to Antarctic magnetic records.

In the diagrams for Sq, some asymmetry is seen between latitudes 28° S and 28° N. Sq(H) at latitude 28° S is not symmetrical with that at latitude 28° N; the range in Sq(E) at latitude 28° S is much larger than that at latitude 28° N. This is probably because the latitudes of the observatories in the group 8 range widely from 12° S to 48° S, extending on both sides of the latitude where Sq(H) reverses its phase. The Sq variations shown in Figs. 5, 6 and 7 are the mean Sq of the years from which the storm records were taken. These Sq variations will be replaced later by those based on Tables B (Sq-tables arranged by storm-time). The Sq variations derived from the Sq-tables by re-arranging according to local time will then represent the mean Sq for the months in which the magnetic storms contributing to the DS variations occurred. Detailed discussions on Sq will be given when such Sq is prepared.

As was explained in Section 1, the changes in the horizontal-force DS are best shown by vectograms. That is, in a rectangular coordinate system, in which E and H are taken as x- and y- axis, the values of DS(E) and DS(H) are plotted for each hour from 0^h to 23^h of local time. These points are connected successively so that the curve obtained represents the trace described by the end of a vector drawn from the origin with length equal to the magnitude of the horizontal-force DS and with the direction of the field. In general, the direction of H is not exactly in the geomagnetic meridian; it also deviates from the geographic north by an angle that is indicated by the declination at each station.

The vectograms of the DS variations are shown in Figs. 8a and 8b. In Fig. 8a the vectograms for groups 5, 6, 7 and 8 are all drawn on the same scale, as is indicated in the diagram. In Fig. 8b, the vectograms for groups 1, 2, 3 and 4 are shown on different scales; the scale in each vectogram is indicated along the arrow showing the geomagnetic north. In all the vectograms the rectangular coordinate axes drawn by full lines represent magnetic coordinates, the magnetic north being vertically upward; the axes drawn by broken lines indicate geographic coordinates, the north being nearly upward; the arrow in each vectogram is directed towards the geomagnetic north. An example of these representations of different coordinates is shown in Fig. 8b. The mean geomagnetic latitudes are also indicated in the diagrams.

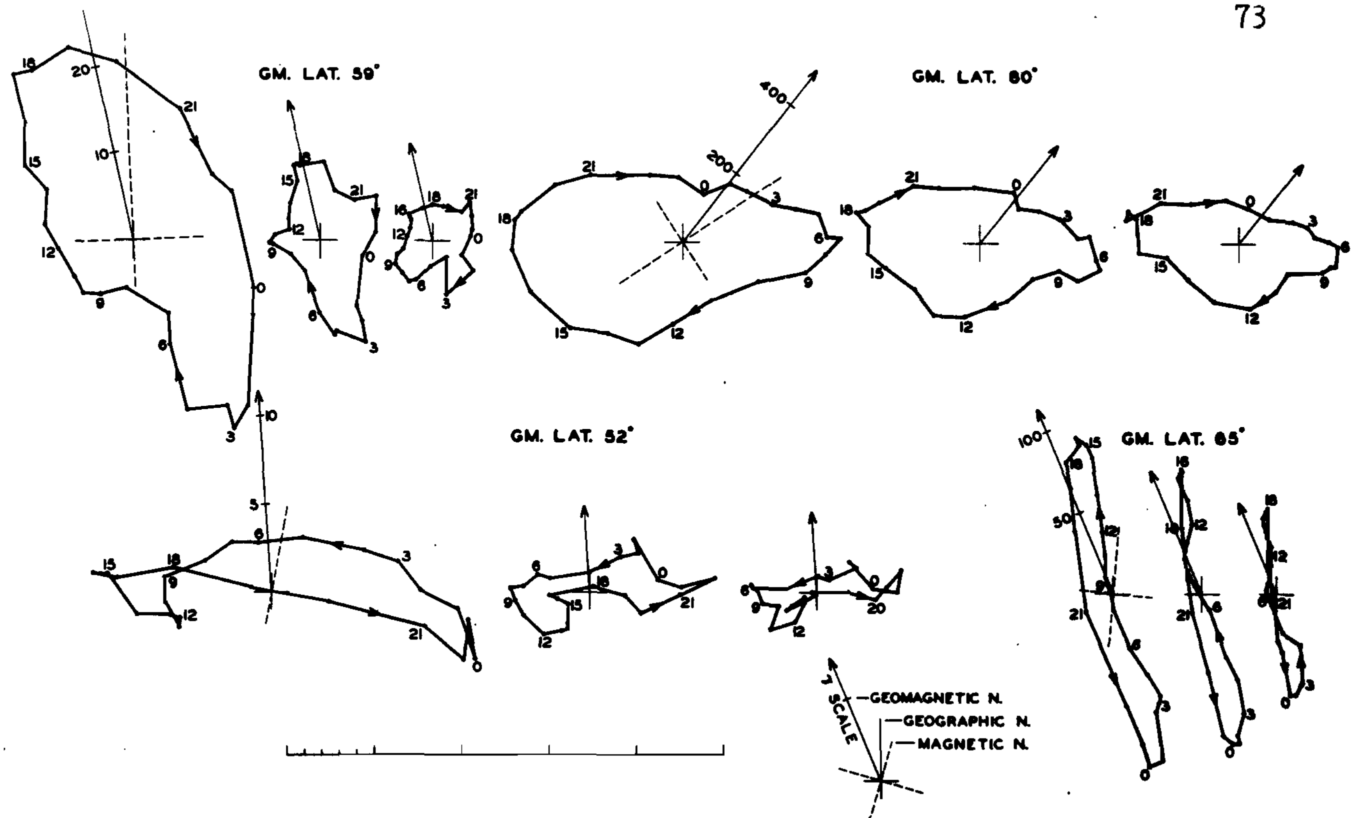

FIG. 8b VECTOGRAMS OF DS

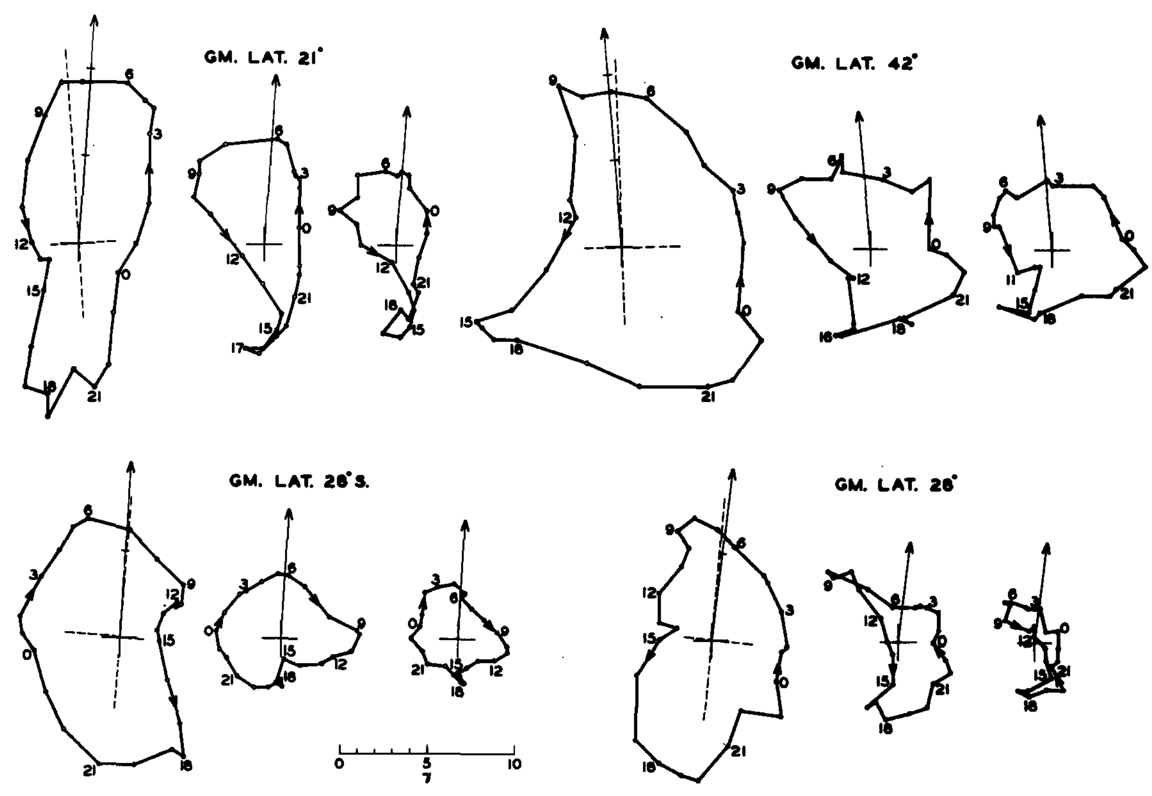

FIG. 8a VECTOGRAMS OF DS

In all groups the decay in DS in the successive three 24-hour intervals is clearly seen. In each latitude there is no material change of type in the course of decay. In Fig. 8a, the direction of rotation changes from clockwise to anticlockwise on crossing the equator northwards. The vectograms are elongated in the direction of the geomagnetic meridian in low latitudes. They tend to take an oval form towards latitude 42°; then with increasing latitude their form becomes elongated in the direction transverse to the geomagnetic meridian. At latitude 52° the vectogram is remarkably flat, indicating that the predominant component in the horizontal-force DS variation is the east-west force. At about latitude 55° the direction of the rotation of the horizontal-force vector is again reversed from anti-clockwise to clockwise in passing northwards. As the auroral zone is approached the elongation of the vectogram changes its direction from the east-west to the direction of the geomagnetic meridian. In the auroral zone (65°) the vectogram is very narrow in the direction parallel to the zone and is elongated in the direction normal to this zone. The maximum poleward force occurs at about 16^{h}, and the opposite minimum at about 0^{h} or 1^{h}. This characteristic form of the vectograms for the stations in the auroral zones is due to electric currents flowing in the ionosphere along the zone in a narrow belt. From the analogy to the jet stream in meteorology, these concentrated electric currents are called the auroral electro-jet. For stations in regions where overhead currents are flowing in a sheet, the vectograms of the horizontal force DS variation take an oval or circular form; whereas under and very near the electro-jet the vectograms become narrow in the direction of the flow of the electro-jet, and elongated in the direction transverse to it. On passing into the polar cap (80°) the vectogram becomes oval again. Comparison of the results described here with those obtained by other workers will be made in Section 9(F).

The DS for eight 6-hour and three 8-hour intervals for each observatory and for groups of observatories for each season was further analyzed harmonically, and was expressed in terms of local time λ_s, or longitude relative to the sun, measured eastwards from the midnight meridian. They are expressed as

$$a_1 \cos \lambda_s + b_1 \sin \lambda_s + a_2 \cos 2\lambda_s + b_2 \sin 2\lambda_s ,$$

or

$$c_1 \sin (\lambda_s + \sigma_1) + c_2 \sin (2\lambda_s + \sigma_2) ,$$

where a, b and c are calculated in gammas for all three elements.

The harmonic coefficients and phases are calculated for each interval of storm-time; hence they are functions of storm-time. The results (a_1, b_1, c_1, σ_1; a_2, b_2) are given in Table 5 at the end of this Section.

The amplitudes and phases of the diurnal components of DS are graphically represented by means of harmonic dials.[32] (The semi-diurnal (12-hour) component is more irregular than the diurnal component; hence the former will not be considered in the present thesis.) That is, each pair of a_1 and b_1 is plotted in a plane coordinate system, in which a_1 is measured upwards, and b_1 to the right. The point will then represent the end of a vector drawn from the origin, with length equal to c_1 and with the direction making the angle σ_1 with the horizontal axis Ob_1. Such harmonic dials were originally drawn for individual stations as well as for various groups of stations for each season separately. But these harmonic dials are not shown here. Figs. 9a and 9b show harmonic dials for the 24-hour component of DS in H, E and V for groups of observatories: (a) for group 8 (see Table 4); (b) for groups 5, 6, 7, and 8; (c), (d), (e), and (f) for groups 4, 3, 2, and 1, respectively. The numerical mean latitude for groups 5, 6, 7, and 8 in (b) is 30°. Mean geomagnetic latitudes for groups (a) to (f) are indicated in parentheses in Figs. 9a and 9b.

When the harmonic analysis was made for some individual observatories in the southern hemisphere, it was clear that DS(H) and DS(V) are symmetrical with respect to the geomagnetic equator and that DS(E) is antisymmetrical. For this reason the signs of the harmonic coefficients for DS(E) for group 8 were reversed in combining with groups 5, 6, and 7. The symmetry in DS(H) and DS(V) and the antisymmetry in DS(E) with respect to the equator can be seen by comparing the dial for (a) to those for (b) and (c).

In the dials for (b) and (c) the phases for E and V exceed those for H by, on the average, 90° for E and 180° for V. This is in good agreement with the results obtained in paper 4 (p. 13). The phase for H and V appears to increase slightly from (b) (latitude 30°) to (c) (latitude 52°), that for E remaining the same.

The phase in DS(V) for the group (a) (28° S) is on the average much closer to that for the group (c) (52° N), than to the corresponding phase for the group (b) (30° N). Although the amplitude of the same variation for the group (a) is about half of that for the group (c), it is much larger than in the group (b). In the horizontal force, both the phase and the amplitude of DS for the group (a) bear also some intermediate characteristics between the groups (b) and (c). In declination these characteristics are not so obvious. These facts again

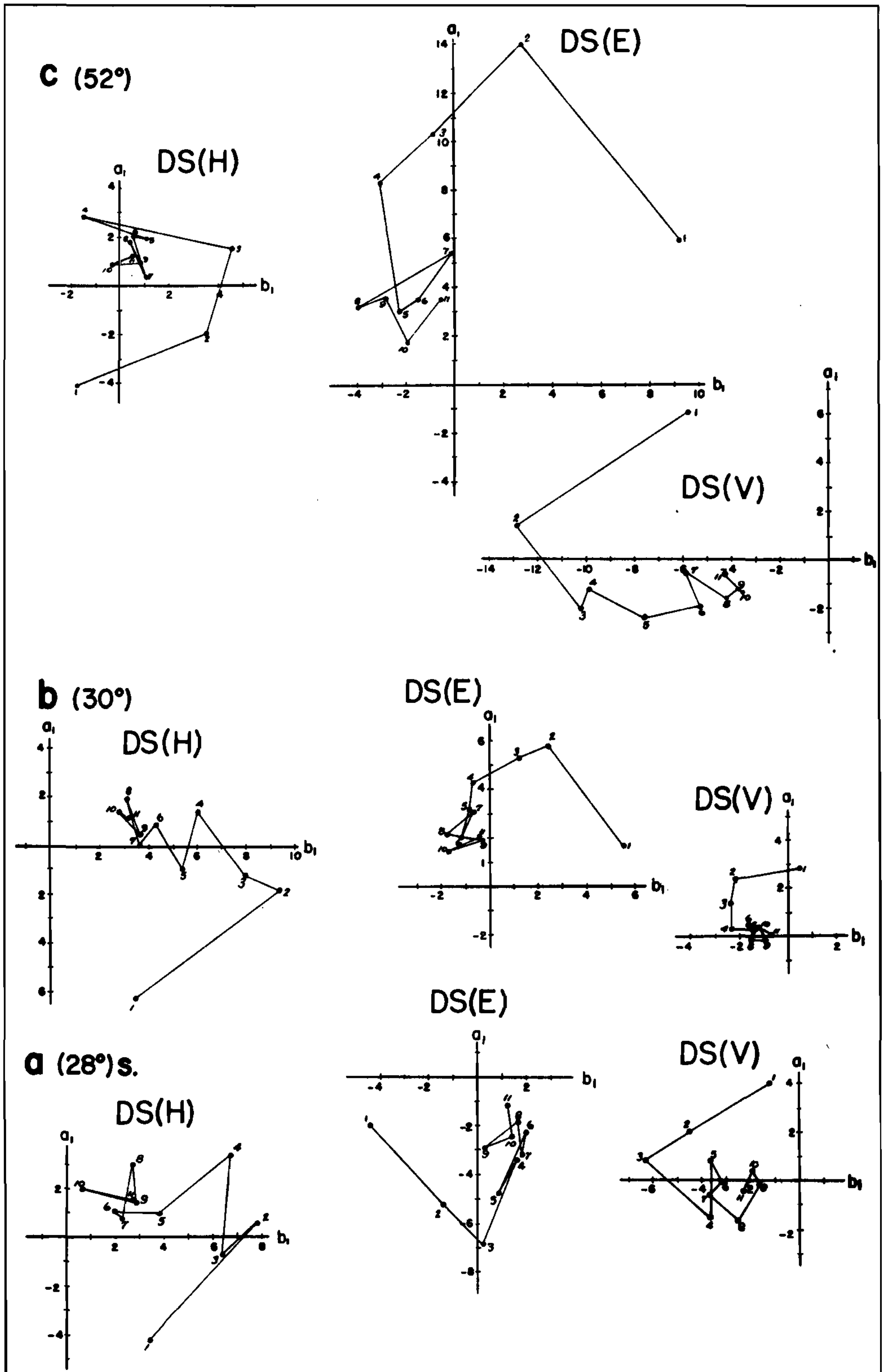

Fig. 9 A. Harmonic dials for DS; gamma

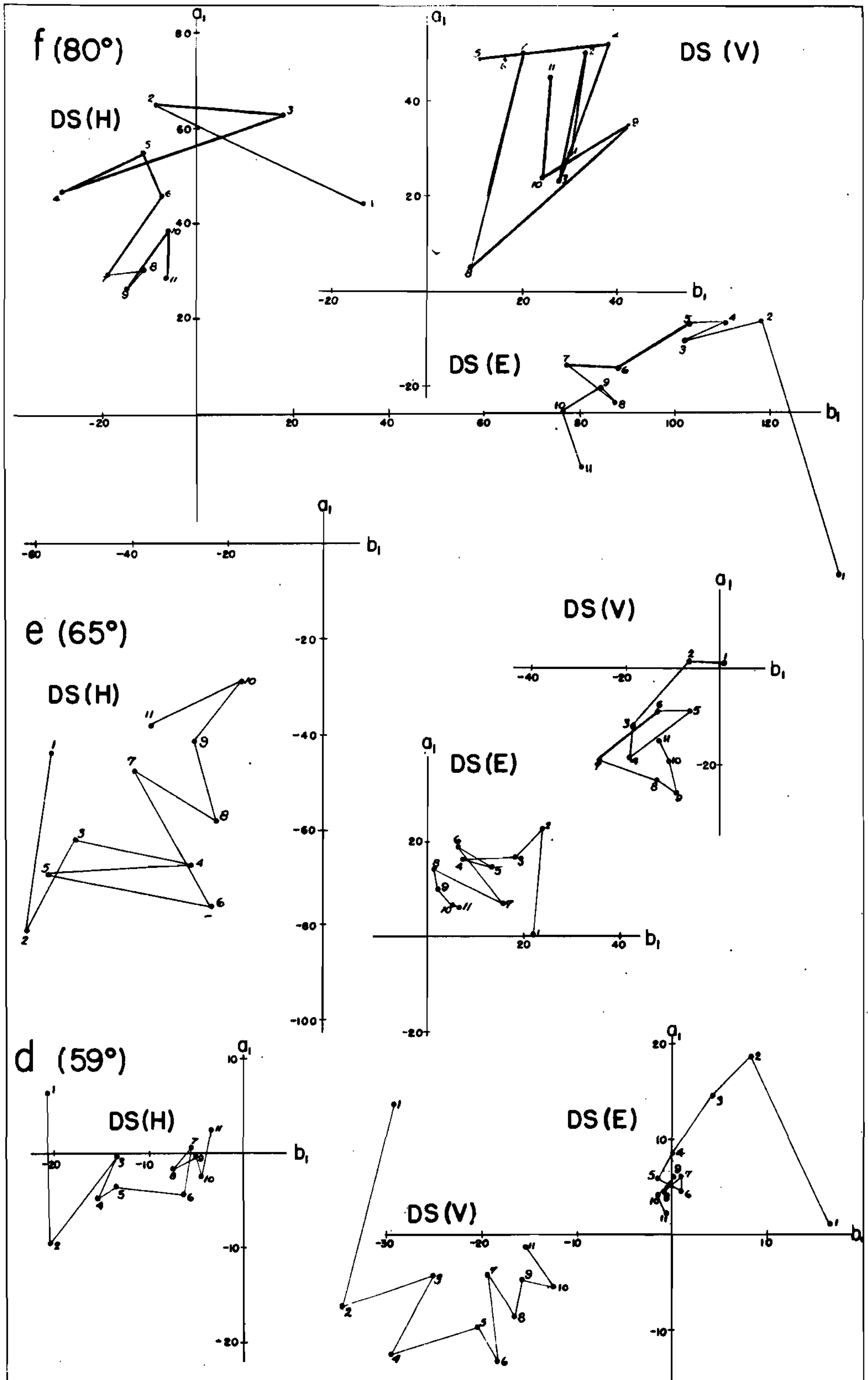

Fig. 9B. Harmonic dials for DS

suggest a possibility that the latitude with respect to which DS(H) and DS(V) are symmetrical (and where DS(Z) reverses its phase) is somewhat to the north of the geomagnetic equator. There is a reversal of phase in H between (c) (latitude 52°), and (d) (latitude 59°), whereas the phase in E remains constant, and for V increases slightly. Consequently in (d) the phases for H and V are nearly the same, and the phase for E is now smaller by about 90° than for H. If the reversal of phase in H from (c) to (d) were considered, for convenience, as an increase in phase by 180°, then the phase for H continues to increase by about 50° on the average from (d) (latitude 52°) to (e) (latitude 59°); the phase in E decreases by about 32°, and in V increases by about 13° on the average. For Godhavn (f) the phase in H is nearly the same as in E in low and middle latitudes (b and c), and the phase in E for Godhavn is nearly the same as in H for these latitudes. The phase in V is reversed from (e) to (f), as is expected from the average DS(V) curves.

We have seen that the amplitude of DS varies widely at different latitudes, and that the way it does so also differs from one element to another. It may be worthwhile showing a simple scheme by which the relative magnitude of DS at various latitudes can be seen at a glance. For this purpose the average amplitude of the diurnal component of DS for each element at different latitudes was expressed in terms of the average amplitude of DS(H) at latitude 30° as unit. That is, $\overline{c_1(X)_s}/\overline{c_1(H)_{5-8}}$ was computed, where $c_1(X)_s$ denotes the c_1 for the element X for group s; the upper bar stands for the mean over the first 72 hours from the storm commencement. The results are shown in Table 6. It should be remembered that the ratios given here are the averages over the period of the first 72 hours, and that hence they give only a crude approximation for the relative magnitude of DS at any particular storm-time. The change in the amplitude (or range) of DS with storm-time at different latitudes will be described in Section 8.

Table 6. The relative magnitude of the 24-hour component of DS (averaged over the first 72 hours of the average weak magnetic storm).

Geomagnetic latitude	30°	52°	59°	65°	80°
H	1.0	0.4	1.9	12.8	9.6
E	0.7	1.2	1.5	3.5	20.0
V	0.4	1.2	4.0	4.0	8.7

In order to obtain smoother harmonic dials for DS, the dials for E and V for groups (b) and (c) (in Figs. 9a and 9b) were combined with H after they were multiplied by their mean ratios to H for each group separately (to make them all nearly of the same size), and also re-oriented, by 90° clockwise for E and by 180° for V. Harmonic dials for these combined sets of variations were found much less irregular than those for individual elements in each group. Then the mean coordinates were taken of the eleven pairs of points. The result is shown in Fig. 10. From its derivation Fig. 10 can be considered as the average harmonic dial for DS(H) for the groups (b) and (c) (mean latitude 41°), the relative size for these two groups being 1.0 to 0.4. At the same time it can be considered as giving approximate harmonic dials for E and V, if it is rotated about the origin through 90° and 180° anticlockwise, respectively, and if the coordinates are multiplied by the following factors. Using Table 6, the factors for E for groups (b) and (c) are found to be $0.7/\frac{1}{2}(1.0+0.4) = 1.0$ and

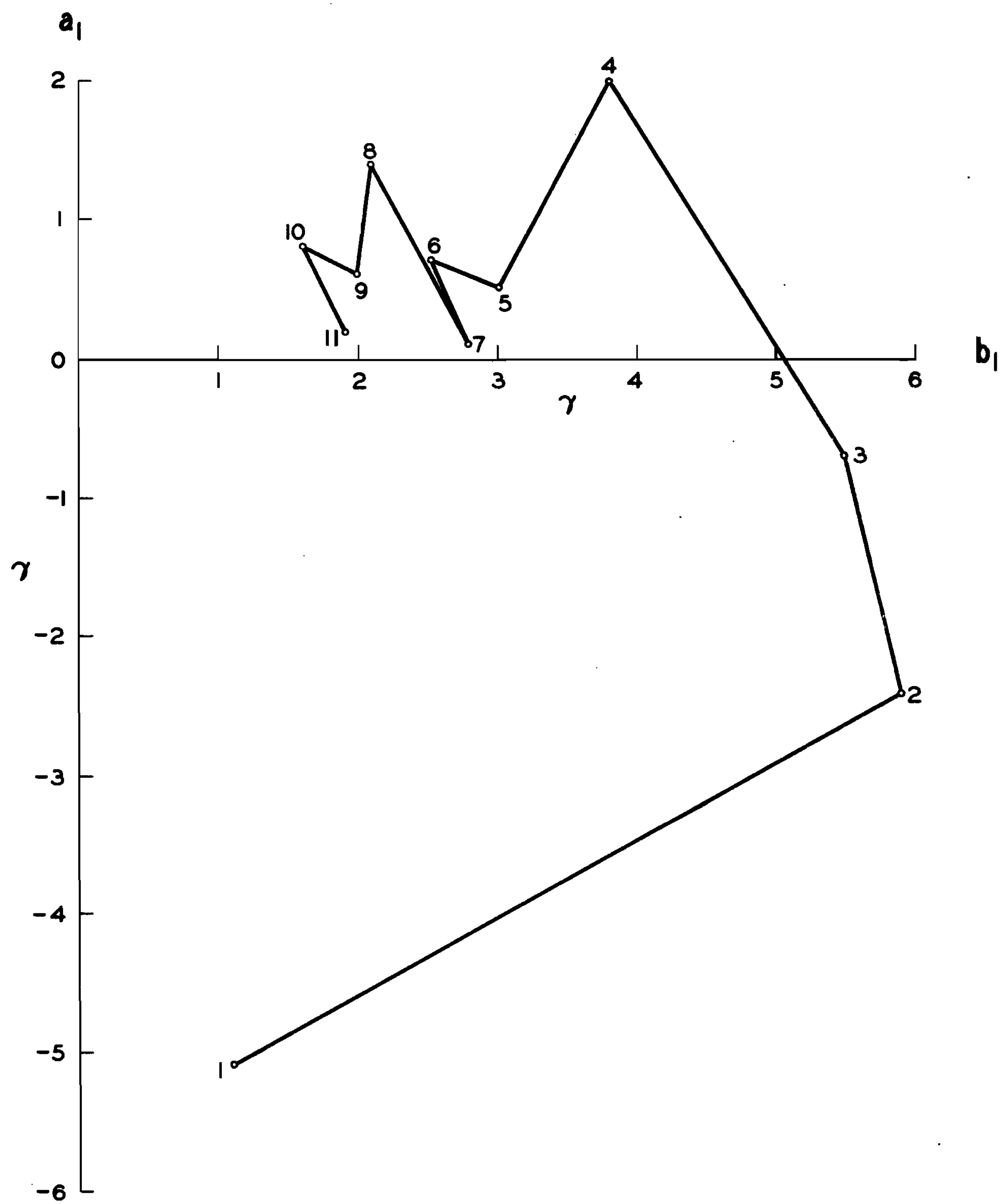

Fig. 10. Harmonic dial for the diurnal component of DS(H); mean of groups 4 to 8 (mean latitude 41°); DS(E), DS(V) combined with DS(H) with modifications in the magnitude and phase.

$1.2/\frac{1}{2}(1.0+0.4) = 1.7$; those for V are $0.4/\frac{1}{2}(1.0+0.4) = 0.6$ and $1.2/\frac{1}{2}(1.0+0.4) = 1.7$, respectively.

Table 5. Harmonic data for the 24-hour component of DS in E, H and V (Unit: gamma). Intervals 1 to 11 refer to 0^h-5^h, 6^h-11^h, 12^h-17^h, 18^h-23^h, 24^h-29^h, 30^h-35^h, 36^h-41^h, 42^h-47^h, 48^h-55^h, 56^h-63^h, 64^h-71^h (storm-time).

Group 1. Godhavn

E

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	-34.2	134.5	139.7	346°	29.8	-22.9
2	19.7	118.4	120.1	9	6.0	-5.4
3	15.1	102.6	103.7	8	-0.6	-4.9
4	19.0	110.9	112.6	10	-4.5	-10.7
5	18.9	103.8	105.5	10	1.4	-17.2
6	9.7	88.2	88.7	6	-1.4	-1.8
7	10.1	77.2	77.9	8	2.9	3.1
8	2.2	87.2	87.2	1	7.5	-3.9
9	5.8	84.7	84.9	4	3.7	-7.9
10	0.6	76.9	76.9	1	1.5	-2.2
11	-11.9	80.0	80.9	352	13.4	6.8

H

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	44.4	34.8	56.4	52	9.8	-40.4
2	65.5	-8.9	66.1	98	-12.0	-17.3
3	63.1	18.1	65.6	74	-22.9	0.7
4	47.0	-28.3	54.8	121	-15.5	0
5	55.7	-11.3	56.8	102	-10.5	-12.2
6	46.6	-7.3	47.2	99	-10.7	2.0
7	29.5	-18.9	35.0	123	0.3	0
8	30.6	-11.2	32.6	110	-3.4	-8.7
9	26.6	-15.2	30.6	120	-2.7	-3.6
10	38.5	-6.0	39.0	99	-14.2	-3.7
11	29.0	-6.7	29.8	103	-3.4	-3.3

V

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	29.9	30.9	43.0	44	-5.9	-6.3
2	50.8	33.8	61.0	56	-6.3	2.8
3	23.6	27.9	36.5	40	7.8	3.8
4	52.5	38.8	65.3	54	0.8	7.8
5	49.1	11.2	50.4	77	-16.1	7.4
6	49.1	16.8	51.9	71	-8.2	4.3
7	50.4	20.3	54.3	68	-6.3	-3.3
8	5.6	9.3	10.9	31	4.9	-1.2
9	35.6	42.5	55.4	40	-19.7	4.3
10	22.0	22.2	31.2	45	-1.3	-1.3
11	45.6	26.3	52.6	60	10.4	-18.4

Group 2. Sodankylä, Tromsö, Lerwick. **E**

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	0.4	22.2	22.2	1°	10.9	7.1
2	23.0	24.5	33.6	43	9.7	10.7
3	16.8	18.9	25.3	42	6.4	5.0
4	16.6	7.5	18.2	66	5.8	3.3
5	15.1	13.6	20.3	48	8.7	10.2
6	19.4	6.5	20.5	72	5.2	6.9
7	6.8	16.0	17.4	23	1.8	3.0
8	14.3	1.5	14.4	84	2.1	5.5
9	9.9	2.3	10.2	77	5.8	2.5
10	6.9	5.6	8.9	51	1.4	3.0
11	6.6	6.4	9.2	46	2.3	6.1

H

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	-44.1	-57.1	72.1	218	-41.3	5.2
2	-81.8	-62.3	102.8	233	-36.4	-0.1
3	-62.2	-52.2	81.2	230	-22.2	14.1
4	-67.9	-27.8	73.3	248	-10.8	9.9
5	-69.4	-57.6	90.2	230	-30.5	3.1
6	-76.3	-23.5	79.8	253	-29.1	-0.4
7	-47.9	-39.2	61.9	231	-21.4	-6.7
8	-58.0	-22.1	62.1	249	-12.4	0.4
9	-41.7	-27.1	49.7	237	-20.1	6.3
10	-28.8	-17.1	33.5	239	-15.0	2.6
11	-36.2	-38.1	52.5	224	-13.8	-15.2

V

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	1.1	0.9	1.4	51	5.2	12.0
2	1.4	-6.7	6.8	168	21.4	7.6
3	-12.8	-18.9	22.8	214	13.8	-8.9
4	-19.5	-18.9	27.2	226	12.8	-0.3
5	-9.4	-6.4	11.4	236	3.8	4.1
6	-9.3	-13.8	16.6	214	5.2	1.7
7	-19.2	-25.8	32.1	217	-2.2	-7.4
8	-23.3	-13.6	27.0	240	3.8	-1.4
9	-26.0	-9.9	27.8	249	-0.9	4.6
10	-19.9	-11.4	22.9	240	-2.3	-3.8
11	-15.4	-13.4	20.4	229	-1.2	-3.6

Group 3. Sitka, Eskdalemuir, Lovö, Rude Skov. **E**

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	1.1	16.5	16.5	4°	4.2	0
2	18.8	8.1	20.5	67	2.6	0
3	14.7	4.1	15.3	75	2.7	1.2
4	8.6	0	8.6	90	1.0	-1.0
5	6.0	-1.4	6.2	103	2.3	1.3
6	4.7	1.0	4.8	78	-0.9	-0.7
7	6.1	1.0	6.2	81	2.0	0.7
8	4.8	-1.0	4.9	102	0.6	0.2
9	6.2	0.1	6.2	89	0.1	0.5
10	4.4	-1.2	4.6	105	-0.7	-0.4
11	2.5	-0.3	2.5	106	1.6	-0.2

H

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	6.6	-20.6	21.6	162	-2.1	-5.8
2	-9.6	-20.4	22.5	205	-4.4	-6.4
3	-0.1	-13.1	13.1	180	-2.3	-2.4
4	-4.9	-15.3	16.1	198	-4.0	-6.5
5	-3.2	-13.6	14.0	193	0.7	-2.3
6	-4.3	-6.1	7.5	215	-2.9	-3.2
7	0.7	-6.6	6.6	174	-0.9	-2.2
8	-1.8	-7.5	7.7	194	0.3	-2.4
9	-0.1	-5.0	5.0	181	-1.6	-0.6
10	-2.4	-4.9	5.5	206	0.6	0.5
11	2.4	-3.3	4.1	144	1.2	-1.2

V

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	13.8	-29.4	32.5	155	3.0	-5.7
2	-7.8	-34.5	35.4	193	-4.4	-7.2
3	-4.5	-25.3	25.7	190	-1.1	-3.1
4	-12.7	-29.7	32.3	203	-1.6	-10.1
5	-9.9	-20.2	22.5	206	-1.6	-2.6
6	-13.3	-18.4	20.8	216	-2.2	-3.5
7	-4.5	-19.5	20.0	193	-0.5	-6.6
8	-8.8	-16.9	19.0	208	-1.4	-6.2
9	-4.9	-15.7	16.5	197	-0.2	-4.5
10	-5.7	-12.6	13.8	204	-0.4	-1.4
11	-1.4	-15.3	15.4	185	-0.7	-5.5

Group 4. De Bilt, Greenwich, Cheltenham, Val Joyeux.

E

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	5.9	9.2	10.9	33°	3.9	-1.4
2	14.0	2.7	14.3	79	2.9	-1.6
3	10.3	-0.9	10.3	95	3.3	-1.2
4	8.3	-3.1	8.9	111	2.3	-0.9
5	3.0	-2.3	3.8	128	1.4	0.1
6	3.5	-1.5	3.8	113	1.9	-0.8
7	5.4	-0.1	5.4	91	1.8	0.1
8	3.2	-4.0	5.1	141	1.0	-0.8
9	3.6	-2.9	4.6	129	1.4	-0.5
10	1.8	-2.0	2.7	138	0.6	-0.7
11	3.5	-0.6	3.6	100	1.9	0

H

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	-4.1	-1.8	4.5	246	-3.8	0.6
2	-1.9	3.5	4.0	332	-1.8	0.8
3	1.5	4.6	4.8	18	-0.4	1.1
4	2.8	-1.5	3.2	118	-2.4	0.8
5	1.9	1.0	2.1	62	-0.8	-0.3
6	2.0	0.5	2.1	76	-0.3	0.5
7	0.4	1.0	1.1	22	0.4	0.9
8	1.8	0.4	1.8	78	-0.9	1.1
9	1.0	0.8	1.3	51	-0.8	0.8
10	0.9	-0.3	0.9	108	0.1	-0.1
11	1.2	0.5	1.3	67	0.1	0

V

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	6.1	-5.8	8.4	134	-1.0	-0.8
2	1.4	-12.9	13.0	174	-2.4	-3.0
3	-2.0	-10.2	10.4	191	-1.2	-0.8
4	-1.3	-9.8	9.9	188	-0.4	-0.1
5	-2.4	-7.6	8.0	198	-1.2	-0.3
6	-1.9	-5.3	5.6	200	-1.0	-0.2
7	-0.5	-5.9	5.9	185	-0.7	-0.8
8	-1.6	-4.2	4.5	201	0.2	-0.8
9	-1.2	-3.8	4.0	198	0	-0.6
10	-1.3	-3.6	3.8	200	-0.6	-0.3
11	-0.6	-4.3	4.3	188	-0.1	-1.2

Group 5. Ebro, Tucson.

E

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	2.6	7.6	8.0	19°	2.7	-0.6
2	9.3	4.2	10.2	66	2.0	-0.2
3	6.7	2.8	7.3	67	2.4	-1.2
4	7.0	-1.1	7.1	99	1.3	-1.1
5	2.7	-2.5	3.7	133	-0.1	-0.1
6	3.0	-0.3	3.0	96	1.2	-1.0
7	4.3	-0.7	4.4	99	2.3	0.2
8	2.5	-3.4	4.2	144	0.8	-0.1
9	3.4	1.7	3.8	63	1.7	-0.5
10	2.1	-2.6	3.3	141	1.4	-0.4
11	3.8	-0.2	3.8	93	1.5	-0.9

H

1	-8.7	5.8	10.5	304	-1.8	-0.5
2	-4.1	9.5	10.3	337	0.3	-1.5
3	0.4	10.1	10.1	2	-0.8	0.1
4	2.7	5.7	6.3	25	-2.2	0.7
5	0.6	5.4	5.4	6	0.9	-0.8
6	1.5	5.9	6.1	14	-0.2	-0.5
7	1.6	5.8	6.0	15	0.4	-0.7
8	1.5	2.2	2.7	34	-1.5	1.7
9	1.9	3.8	4.2	27	-0.5	0.3
10	1.2	3.5	3.7	19	0.6	-0.3
11	0.1	3.6	3.6	2	0.7	0.9

V

1	3.9	1.1	4.1	74	-0.1	0.1
2	4.4	-3.8	5.8	131	-0.2	-0.8
3	2.1	-2.4	3.2	139	0.7	-0.9
4	1.8	-4.3	4.7	157	-0.2	0
5	0.2	-3.9	3.9	177	-0.1	0
6	0.2	-2.5	2.5	175	0	-0.2
7	1.1	-1.5	1.9	144	0.9	-0.8
8	0.2	-2.7	2.7	176	0.4	-0.1
9	0.1	-2.6	2.6	178	0.4	0
10	0	-2.2	2.2	180	0	-0.8
11	1.4	-1.2	1.8	131	-0.3	-0.7

Group 6. San Juan, Kakioka.

E

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	-0.1	4.8	4.8	359°	1.5	-0.2
2	5.1	2.8	5.8	61	1.0	0.2
3	4.4	1.3	4.6	74	0.7	0.7
4	3.7	-0.5	3.7	98	0	0.3
5	2.3	0.3	2.3	83	0.8	1.0
6	2.1	-0.8	2.2	111	0.5	0.5
7	2.5	-0.8	2.6	108	0.6	0.9
8	2.0	-0.5	2.1	104	0.6	-0.1
9	-0.1	-0.9	0.9	186	1.3	0.1
10	0.8	-1.3	1.5	148	0.9	-0.5
11	1.5	-0.2	1.5	98	0	0.2

H

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	-6.7	-0.2	6.7	268	-0.6	0.2
2	-2.4	10.5	11.0	342	0.2	-0.1
3	-2.4	6.3	6.7	339	1.1	0.7
4	-1.5	5.8	6.0	346	1.1	-0.4
5	-2.9	5.6	6.3	333	1.6	-0.6
6	0.3	3.9	3.9	4	1.1	-0.6
7	-2.7	2.2	3.5	309	0.9	-0.4
8	0.7	2.0	2.1	19	-0.4	-0.5
9	-1.6	3.4	3.8	335	0.8	0
10	1.1	2.5	2.7	24	0.5	-0.2
11	0.6	2.3	2.4	15	-0.5	0.1

V

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	2.2	1.1	2.5	63	-0.9	-0.3
2	3.1	0.3	3.1	85	-0.3	-0.2
3	1.5	-1.1	1.9	126	0.5	0.5
4	0.9	-0.2	-.9	103	0.8	-0.4
5	1.3	0.9	1.6	55	0.1	-0.3
6	1.4	0.3	1.4	78	1.0	-0.7
7	0.8	-0.3	0.9	111	0.3	-0.6
8	0.7	-0.9	1.1	142	0.1	-0.3
9	-0.2	1.3	1.3	351	0	0
10	1.0	0.2	1.0	79	0	-0.3
11	0.4	0.3	0.5	53	0.3	0.4

Group 7. Honolulu, Zikawei. **E**

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	2.3	4.7	5.2	26°	-0.8	-0.1
2	3.7	1.1	3.9	74	0.1	1.6
3	3.1	0.8	3.2	76	0.8	1.2
4	2.9	0.3	2.9	84	-0.2	0.7
5	2.9	-0.5	2.9	100	0.3	1.7
6	0.5	-1.5	1.6	162	0.3	1.5
7	2.5	0.4	2.5	81	0.1	0.7
8	2.4	-1.4	2.8	120	0.4	0.6
9	1.3	-1.6	2.1	141	0.5	0.9
10	0.7	-1.6	1.7	156	0.5	0.9
11	1.6	-0.1	1.6	94	0.1	0.5

H

1	-5.7	5.1	7.6	312	-1.1	1.3
2	-1.9	9.9	10.1	349	-1.6	-0.1
3	-2.2	9.4	9.7	347	0.3	0.1
4	1.4	10.4	10.5	8	0.2	0.8
5	-2.7	6.7	7.2	338	0.5	-0.3
6	0.9	5.5	5.6	9	0.2	0.2
7	0.6	5.6	5.6	6	0.1	-1.0
8	2.3	5.3	5.8	23	-0.3	-0.5
9	0.2	4.6	4.6	3	0.4	0.2
10	1.3	4.4	4.6	16	0.4	-0.6
11	2.0	4.7	5.1	23	0.1	-0.3

V

1	1.4	0.9	1.7	57	0.2	0.9
2	-0.2	-0.6	0.6	198	1.3	1.1
3	0.7	0.6	0.9	49	0.9	0.6
4	-0.1	-1.0	1.0	186	1.0	-0.1
5	-0.8	0.6	1.0	307	1.1	0.3
6	0.5	-1.0	1.1	153	1.0	0.7
7	0.4	-0.5	0.6	141	0.9	0.1
8	0.4	0.4	0.6	45	0.6	0.1
9	-0.2	-0.6	0.6	198	0.4	0
10	0.5	-0.9	1.0	151	1.0	0.7
11	-0.9	0.3	0.9	288	0.4	-0.3

Group 8. Southern stations combined. E

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	-2.0	-4.4	4.8	204°	-1.8	0.2
2	-5.3	-1.4	5.5	255	-1.1	-0.6
3	-7.1	0.2	7.1	272	-1.0	-1.6
4	-3.4	1.6	3.8	295	-1.1	-0.4
5	-4.7	0.9	4.8	281	-1.1	-0.6
6	-2.3	2.0	3.0	311	0	0
7	-3.2	1.8	3.7	299	0.3	-0.9
8	-1.8	1.7	2.5	313	-0.2	-0.6
9	-2.9	0.3	2.9	276	-0.4	0.1
10	-2.5	1.4	2.9	299	0	0
11	-1.1	1.2	1.6	318	-0.4	-0.8

H

1	-4.2	3.4	5.4	309	1.0	2.0
2	0.6	7.8	7.8	4	0.6	1.3
3	-0.8	6.3	6.4	353	1.0	1.5
4	3.4	6.7	7.5	27	0.7	0.7
5	1.0	3.8	3.9	15	0.2	1.7
6	1.1	1.9	2.2	30	-0.4	0.2
7	0.8	2.3	2.4	19	0.4	1.3
8	3.0	2.7	4.0	48	-0.3	-0.1
9	1.4	2.9	3.2	26	1.0	0.3
10	2.0	0.6	2.1	73	0.3	0.7
11	1.5	2.7	3.1	29	-0.8	0.6

V

1	4.0	-1.3	4.2	108	0	-0.6
2	2.1	-4.5	5.0	155	0.6	-0.4
3	1.1	-6.3	6.4	170	0	0.3
4	-1.5	-3.7	4.0	202	0.4	-0.5
5	0.8	-3.7	3.8	168	-0.1	-0.8
6	-0.1	-3.2	3.2	182	0.1	0.4
7	-0.6	-3.7	3.7	189	0.2	0.3
8	-1.7	-2.7	3.2	212	0.2	0.5
9	-0.2	-1.7	1.7	187	-0.3	-0.4
10	0.4	-1.9	1.9	168	-0.2	0
11	-0.5	-2.3	2.4	192	0.6	0

Groups 5, 6, 7 and 8 combined. **E**

Interval	a_1	b_1	c_1	σ_1	a_2	b_2
1	1.7	5.4	5.6	18°	1.3	-0.3
2	5.8	2.4	6.3	68	1.0	0.5
3	5.3	1.2	5.4	77	1.2	0.6
4	4.3	-0.7	4.4	99	0.6	0.1
5	3.1	-0.9	3.2	106	0.5	0.8
6	2.0	-1.2	2.3	121	0.5	0.3
7	3.1	-0.7	3.2	103	0.7	0.7
8	2.2	-1.8	2.8	129	0.5	0.3
9	1.9	-0.3	1.9	99	1.0	0.1
10	1.5	-1.7	2.3	139	0.7	0
11	2.0	-0.4	2.0	101	0.5	0.2

H

1	-6.3	3.5	7.2	299	-0.6	0.8
2	-1.9	9.4	9.6	349	-0.1	-0.1
3	-1.3	8.0	8.1	351	0.4	0.6
4	1.4	6.1	6.3	13	-0.3	0.3
5	-1.0	5.4	5.5	350	0.8	0
6	0.9	4.3	4.4	12	0.2	-0.2
7	0.1	3.9	3.9	1	0.5	-0.2
8	1.9	3.1	3.6	32	-0.6	0.2
9	0.5	3.7	3.7	8	0.4	0.2
10	1.4	2.8	3.1	27	0.5	-0.1
11	1.1	3.3	3.5	18	-0.1	0.3

V

1	2.9	0.5	2.9	80	-0.2	0
2	2.4	-2.2	3.3	133	0.4	-0.1
3	1.4	-2.3	2.7	149	0.5	0.1
4	0.3	-2.3	2.3	173	0.5	-0.3
5	0.4	-1.5	1.6	165	0.3	0.2
6	0.5	-1.6	1.7	163	0.5	0.1
7	0.4	-1.5	1.6	165	0.6	-0.3
8	-0.1	-1.5	1.5	184	0.3	0.1
9	-0.1	-0.9	0.9	186	0.1	-0.1
10	0.5	-1.2	1.3	157	0.2	-0.1
11	0.1	-0.7	0.7	172	0.3	-0.2

8. Comparison of the rates of growth and decay of Dst and DS.

The rates of growth and decay of Dst and DS are now compared for various epochs of the average weak magnetic storm at different latitudes. In Fig. 11, Dst and the range ($2c_1$) of DS for H, E and V are plotted against storm-time for the groups of observatories, (b), (c), (d), (e) and (f), the grouping being the same as in Fig. 9. The range of DS, which is always positive, is plotted with reversed sign to compare with Dst in H. Scales are the same for H, E and V in each group; but they are different in (b,c), (d), (e), and (f).

In Fig. 11 all curves except for V at high latitudes (e and f) show that DS attains its maximum before 12^h (probably at about 8^h) and decays more rapidly than Dst. In Figs. 11 (b), (c) and (d), ranging in latitude from 30^o to about 60^o, DS recovers nearly to a half of its maximum at about 30^h or before. In the auroral zone (e) recovery of DS for H and E is delayed compared with that to the south of the zone, a half of its maximum being reached at about the end of the second day. Over the auroral cap (within the auroral zone) (f) the recovery of DS appears to be delayed more than in the zone. In general, the vertical force DS appears to recover more slowly than H and E.

As seen in Fig. 4, Dst(H), which is the main component of the storm-time variation, attains its minimum at the end of the first day, or in the second day, and has recovered only by a few gammas or less at the end of the third day, south of the auroral zone. In and within the auroral zone Dst(H) seems to maintain its minimum level through the second and third days. It appears clear that DS, on the whole, follows a course materially different from that of Dst at all latitudes.

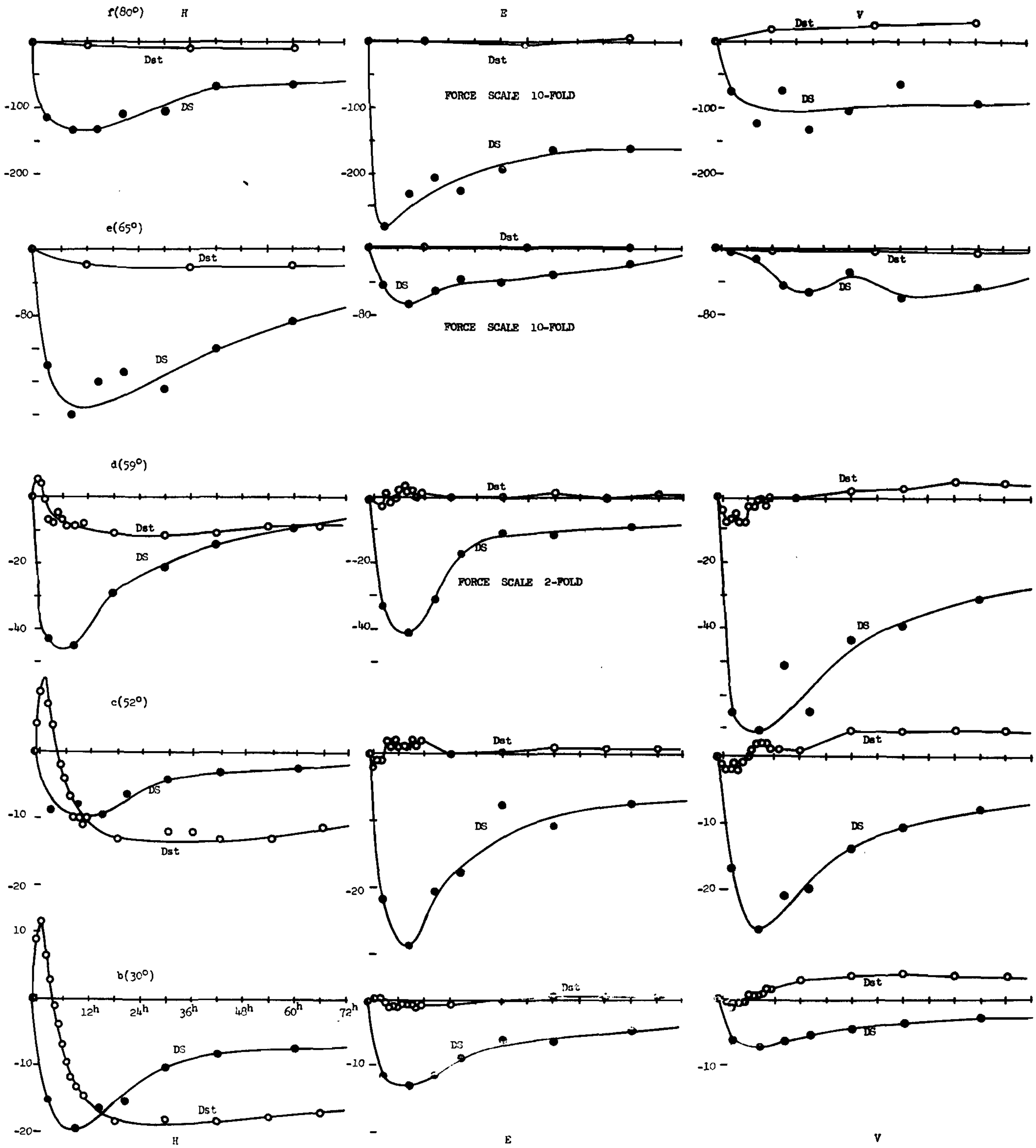

Fig. 11. Rates of growth and decay of Dst and DS for H, E and V at various latitudes.

9. Discussions and conclusion.

(A) The average class number of 136 weak magnetic storms used in this study is 16 (15 for season d, 16 for both seasons j and e). From Figs. 11(b) and 11(c) the average Dst(H) at latitudes 30° and 52° is about 19 gammas and 13 gammas, respectively. If the mean of these two groups is taken, the average Dst(H) at low and middle latitudes is about 16 gammas. The new method of classification of magnetic storms described in Section 4 was based on the maximum diminution in the horizontal force at low and middle latitudes. The agreement of the mean class number with the mean minimum H shows that this method is successful on a statistical basis.

(B) In the present work hour-to-hour differences of the magnetic data were used, instead of hourly values or relative values derived from them and reckoned from some fixed level. Two main reasons why the data were treated on an hour-to-hour difference basis have already been explained briefly in Section 5. The majority of the hourly values given in observatory reports are three-digit numbers. If these were copied directly, for the 136 storms studied in this paper, a modest estimate of the total number of digits to be transcribed from observatory reports to Table A alone would be about $1\frac{1}{2}$ million; the whole process of analysis would require an incredible amount of work. If, however, hour-to-hour differences are used, the numbers dealt with are on the average much smaller, and the time and labor involved in the work are considerably reduced. Another advantage of this method is that it provides a convenient check at each step in analysis. This can be illustrated by the following simple example.

Let us suppose that we have an "information" that is completely described by a set of numbers

$$a_o, a_1, a_2, \ldots\ldots, a_n.$$

The same amount of information can also be specified by another set of numbers

$$a_o, a_1-a_o, a_2-a_1, \ldots\ldots, a_n-a_{n-1}.$$

Let these numbers be denoted by

$$d_o, d_1, d_2, \ldots\ldots, d_n.$$

Then obviously

$$\sum_{i=0}^{n} d_i = a_n,$$

or

$$\sum_{i=1}^{n} d_i = a_n - a_o.$$

This is what has just been said above.

The following explains the reason why the procedure based on an hour-to-hour difference basis simplifies the treatment of missing entries. Let us suppose that a set of magnetic hourly values for element X are given according to some time reference, and that we are interested in the variation of X measured from the level of X at $t = t_o$. The values may be tabulated in the following way:

t_o	t_1	$t_2 \ldots\ldots t_n$
X_{10}	X_{11}	$X_{12} \ldots\ldots X_{1n}$
X_{20}	X_{21}	$X_{22} \ldots\ldots X_{2n}$
X_{30}	X_{31}	$X_{32} \ldots\ldots X_{3n}$
$\vdots$		$\vdots$
X_{m0}	X_{m1}	$X_{m2} \ldots\ldots X_{mn}$

In this table each row refers to a set of observations at times $t = t_o$,

t_1, t_2, ..., t_n of the variation in X, say, a magnetic storm variation in X. X_{ij} ($i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$) therefore, is the value of X for storm i at $t = t_j$. We wish to determine the mean variation of X reckoned from the level at $t = t_o$. The easiest way to obtain such variation is first to form the mean in each column. That is,

$$\text{for } t = t_o: \quad \overline{X}_o = \sum_{i=1}^{m} X_{io}/m,$$
$$\text{for } t = t_1: \quad \overline{X}_1 = \sum_{i=1}^{m} X_{i1}/m,$$
$$\ldots \qquad \ldots$$
$$\text{for } t = t_n: \quad \overline{X}_n = \sum_{i=1}^{m} X_{in}/m,$$

where the upper bar indicates the average over the subscript i. The average variation reckoned from the level at time t_o is then obtained simply by subtracting $\overline{X}_o$ from $\overline{X}_1$, $\overline{X}_2$, ..., $\overline{X}_n$. If this average variation is denoted by Y_o, Y_1, Y_2, ..., Y_n, then we have

$$Y_o = 0,$$
$$Y_1 = \overline{X}_1 - \overline{X}_o,$$
$$Y_2 = \overline{X}_2 - \overline{X}_o,$$
$$\ldots$$
$$\ldots$$
$$Y_n = \overline{X}_n - \overline{X}_o.$$

Now, the original table can be re-written in the following way:

t_o	t_1	t_2	t_n
X_{10}	$X_{10}+x_{11}$	$X_{10}+x_{12}$	$X_{10}+x_{1n}$
X_{20}	$X_{20}+x_{21}$	$X_{20}+x_{22}$	$X_{20}+x_{2n}$
.			.
.			.
.			.
X_{mo}	$X_{mo}+x_{m1}$	$X_{mo}+x_{m2}$	$X_{mo}+x_{mn}$

By forming columnar means, we have

$$\overline{X}_0 = \sum_{i=1}^{m} X_{i0}/m,$$

$$\overline{X}_1 = \overline{X}_0 + \sum_{i=1}^{m} x_{i1}/m,$$

$$----$$

$$----$$

$$\overline{X}_n = \overline{X}_0 + \sum_{i=1}^{m} x_{in}/m.$$

Abstracting $\overline{X}_0$ from each of these means, we have for Y_0, Y_1, ..., Y_n,

$$Y_0 = 0$$

$$Y_1 = \overline{x}_1$$

$$Y_2 = \overline{x}_2$$

$$\ldots$$

$$Y_m = \overline{x}_m,$$

where

$$\overline{x}_k = \sum_{i=1}^{m} x_{ik}/m.$$

Comparing these two results for Y, we can see that if we form the columnar means from the original table for X and subtract the mean determined for time t_o from all the values, the results are exactly the same as the results that are obtained from the data in which X is measured from the value at time t_o in each individual case. This is obvious, if there is no missing data in the original table. Let us suppose now that the table contains a missing entry, say, X_{12}. Then, forming columnar means for $t = t_o$, t_1, ..., t_n, we have exactly the same result as before except for $t = t_2$. If the data were complete we have

$$\overline{X}_2 = \sum_{i=1}^{m} X_{i2}/m.$$

But, now on account of the missing entry,

$$\overline{X}_2 = \frac{X_{22}+X_{32}+\cdots+X_{m2}}{m-1}.$$

If we simply subtract $\overline{X}_o$ from this we get

$$Y_2 = \frac{X_{22}+X_{32}+\cdots\cdots+X_{m2}}{m-1} - \overline{X}_o.$$

On the other hand, if we use the data reckoned from the level at time t_o in each case, then we have for Y_2:

$$Y_2' = \frac{x_{22}+x_{32}+\cdots\cdots+x_{m2}}{m-1}$$

The prime was used to distinguish Y so obtained from the previous Y_2. Y_2' is clearly not equal to Y_2, or

$$Y_2 = Y_2' + \frac{\sum_{i=1}^{m} X_{io} - mX_{10}}{m(m-1)} .$$

We are of course interested in Y', rather than in Y. There is no complication arising from missing data, if all the values are measured from the level at time t_o for each case. However, when a large amount of data are dealt with, such reconstruction of tables of hourly values usually involves heavy labor. Of course, it is possible, for instance, in the above example to form the mean of X_{io} excluding X_{10}, and subtract it from the ordinary columnar mean for time t_2. This process, however, also involves considerable amount of labor especially when the hourly values are re-arranged according as a different time reference.

Now, if hour-to-hour differences are used, such complications do not enter at all throughout the process of analysis. This is because these differences refer only to pairs of neighboring values, and are independent of the initial level, though they can be referred to such level by an appropriate method.

(C) Since the numerical work involved in the present work is extremely laborious, the question of whether or not it could be done by means of punched cards was seriously considered. In order to test this possibility, a trial was made with the data for the forty-two weak storms in season d for the element H for Honolulu. The hourly values and all the necessary information on the storms such as serial numbers, season, intensity, times of commencements, etc., were punched on IBM cards. These data were then printed on paper. This trial was made at the U.S. Coast and Geodetic Survey, the Department of Commerce, Washington, D.C. over a short period of time, and under the circumstances prevailing at that time it was not possible to proceed further. Although the method proved to be useful in transcribing the data from published records, it was concluded that the IBM punched card method would require many re-punching processes in the later phases of the work; e.g. in determining DS for short intervals of storm-time. It may not be impossible, however, to carry out the work by the punched card method, if enough funds and necessary facilities are available at hand. But it appears rather questionable if one can save time by using such a method. Also, the treatment of missing entries may cause considerable difficulties.

(D) The average storm-time field will next be considered. The magnitude of Dst(H) decreases with increasing geomagnetic latitude to about latitude 60°, where it attains its minimum, and increases rapidly to its second peak in the auroral zone. Within the auroral zone, that is, in the polar cap, Dst(H) diminishes again towards the geomagnetic north pole. Dst(E), if defined as the departure transverse to the geomagnetic north in the unit of force, is very small in all latitudes, implying that the Dst field lies nearly in the geomagnetic meridian. The uncertainty in this is of the order of 1 or 2 gammas in all latitudes up to about 60°. The minimum of Dst(H) at latitudes 21°, 28°, 42°, 52° and 59° was found to be 25, 19, 15, 13 and 12 gammas, respectively. If the Dst-field is assumed to be parallel to the geomagnetic axis, the intensity of this field at these latitudes is 27, 22, 20, 21 and 23 gammas, respectively. On this assumption, therefore, the minimum of the whole Dst-field appears to be reached at about latitude 42° with an uncertainty of about 5° on both sides. If the Dst-field that is causing a large diminution in H under the auroral zone gives any appreciable influence on the Dst(H) at 52° and 59°, the assumption made above must be modified at these latitudes. Consequently, the latitude of the minimum Dst-field may have to be altered. However, considering the fact that Dst(V) at these latitudes does not differ from that at lower latitudes, it is unlikely that this is the case.

The storm-time variations in the southern hemisphere shown in Fig. 4a confirm the view that Dst(H) is symmetrical with respect to the geomagnetic equator and that Dst(Z) is antisymmetrical. As to E, no systematic change is seen at either northern or southern stations. There is no significant difference between the storm-time variations at about 30° north and south of the equator.

The recovery in Dst(H) found in this paper appears much slower than that shown in paper 1. This is probably because the magnetic storms there used were of greater average intensity than those used here. In Fig. 2 in paper 4 the mean Dst(H) at its minimum is about -35 gammas for the eight observatories (mean latitude 38°); whereas minimum Dst(H) of the average weak magnetic storms dealt with in this paper is about -16 gammas at the corresponding latitude. It is known that the more intense a magnetic storm, the earlier is the epoch of minimum H in Dst. The slow recovery of the average weak storm may prove that this holds for magnetic storms of much weaker intensity than those used in 1. It should also be noted that in this paper allowance was made for the non-cyclic variation; but in 1 it was not. The non-cyclic variation in H is a steady increase, and if (as in paper 1) it is not removed from the data, this will make the recovery of Dst(H) appear quicker than if, as in this paper, it is removed. In Moos' discussion[3] he showed the Dst variation in H corrected for non-cyclic variation for the two groups of 113 and 134 magnetic storms. Though it is not clear how the correction was made, the corrected Dst curves show considerably slower recovery than the uncorrected curves.

In this respect, however, an important remark on the non-cyclic variation has been made recently by R.P.W. Lewis[30]. He compared the plots of monthly or daily mean H with the corresponding plots of the international character-figure C, and found that long-continued increases of H were associated not with long quiet periods, but with a steady decrease in the average level of activity. He chose 105 periods of not less than thirty-hour duration from the years 1940 to 1947, such that the international planetary index Kp was never greater than 1+. The progress of H during these intervals was studied with magnetic results from Watheroo and Huancayo by taking the consecutive 24-hour non-cyclic variations that were wholly included in each quiet interval. The results showed that any departure of the non-cyclic variation from constancy with time was not demonstrable, and that the standard errors were too large for any estimate to be made of the rate of change. Then, using the results obtained by Lewis and D.H. McIntosh(31), he attempted to determine the rate of decay of the post-disturbance effect. He studied the average effect of a day of peak magnetic Kp disturbance on the horizontal force at Eskdalemuir. He found that the effect manifests itself in the horizontal force as a delayed and assymmetrical trough. The latter part of this trough was found to fit well an exponential curve, indicating slow recovery to a level appropriate to the moderate and approximately constant disturbance that preceded and followed the isolated peak. According to his estimate, the time-constant of decay of the slow recovery of the horizontal force (i.e. the time in which the depression in H diminishes to 10 per cent of its initial value) is about two days. He concluded that long-continued increases in the horizontal force that occur in practice are due simply to a slow change from high to low magnetic activity. If this view is correct, the treatment of non-cyclic variation here adopted may possibly not be appropriate. Definite conclusion on this problem, however, must await a more thorough investigation.

(E) In the DS variations for the first, second, and third storm days, and also in the harmonic dials for the diurnal component of DS, it was seen that the DS variation for H is not symmetrical with respect to the geomagnetic equator, and that the DS variation for Z does not reverse its phase there. It appears that the turning point is located somewhat to the north of the equator, probably between latitudes 10° and 20°. In this study, however, the seven southern stations, ranging in latitude from 12° to 48° were combined all together. In the case of Sq, therefore, the range contains the latitude where the horizontal force reverses phase; this makes the interpretation of the average Sq variations for these southern stations extremely difficult. In order to study the Sq variations on both sides of the latitude of the phase reversal in H, and also to examine more thoroughly the position of the turning point in DS, it appears to be necessary to subdivide the group of these southern stations. The reversal of phase in DS(H) was found to occur near latitude 52°. As has already been mentioned in Section 7, it may be possible to determine the latitude of this reversal more closely by subdividing the storms. It will also be interesting to examine the change of this latitude of reversal with storm intensity.

(F) The vectogram for the group of observatories whose mean geomagnetic latitude is 52° shows that its form is very narrow in the direction along the magnetic meridian and is elongated in the direction transverse to it. This character is maintained throughout the three storm days. It will be of some interest to compare these vectograms with those for SD as derived from slight disturbance.

The vectograms for DS at latitude 59° resemble those drawn for disturbed days at Eskdalemuir and Lerwick, but are more elongated. It appears that all these vectograms are elongated nearly in the direction of the magnetic meridian.

The vectograms for latitude 65° resemble those drawn by Chapman for Sodankylä (64°) and Bossekop (67°) from the SD variations (all-days minus quiet-days). They are very narrow in the direction parallel to the auroral zone, and are elongated in the direction normal to the zone. The maximum poleward force occurs at about 16^h and the opposite minimum at about 0^h in all cases. In the paper already referred[10], Vestine and Chapman showed the vectograms for stations in polar regions. These were drawn for the SD variations, as derived from international disturbed days minus international quiet days, with the material mainly obtained during the Second International Polar Year, 1932-3. The vectograms for Sodankylä (64°), Petsamo (65°), Tromsö (67°), Dickson (63°) are quite similar to that shown in Fig. 8b in this paper, but they are more irregular than the latter. There is an obvious tendency for the minimum of the poleward force to occur later (1^{h} to 4^{h}) in SD than in DS. In the same paper they showed a vectogram for Godhavn for SD. It is nearly circular, whereas the vectograms for this station shown in Fig. 8b are elongated in the direction transverse to the magnetic (not geomagnetic) meridian. In the diagrams shown by Vestine and Chapman, the vectogram for Franz Josef Land (72°) slightly bears this tendency, but it is more elongated in the direction mentioned above, and is considerably irregular. The vectogram for Chesterfield Inlet (74°) is to some extent similar to that for Franz Josef Land; but the direction of elongation is more tilted towards the direction along the geomagnetic meridian. For Scoresbysund (76°) the form of the vectogram is very irregular, but we are perhaps not likely to be seriously mistaken if we consider the form of vectogram for this station as an intermediate type between Godhavn and Chesterfield Inlet or Franz Josef Land. If so, the oval form of the vectogram for DS at Godhavn (shown in Fig. 8b) suggests that during magnetic storms the auroral zone is more extended polewards as well as southwards. There is evidence, though not shown here, that when the vectogram for this station is drawn for shorter intervals for each season separately, it tends to start with a form narrow in the direction of the magnetic meridian (and much elongated in the direction transverse to it), and to become more and more oval as the storm develops; towards the end of the third day of the storm, the vectogram again resumes the elongated form. This change in the form of vectogram for Godhavn with storm time should be investigated more thoroughly with more storms.

(G) Remarkable seasonal changes have been found in DS in high latitudes; they become less notable with decreasing latitude. It is hoped that these seasonal changes in DS, as well as in Dst, if any, will be investigated thoroughly by dividing the 136 weak storms used here into seasonal subgroups. Very little information has been gained on the characteristics of Dst and especially DS during great storms, compared with what is known for weak and moderate storms. An extension of the present study to 136 active and 74 great storms is now being undertaken in order to improve our knowledge on the morphology of magnetic storms.

(H) In conclusion, the final objectives of the present study will be discussed. In paper 1 Chapman proposed an electric current system that can qualitatively explain the average disturbance daily variations. This current system was however too simple to represent the observed facts; for instance, it did not include the electro-jets flowing along the northern and southern auroral zones. In paper 2, he investigated the characteristics of the disturbance daily variations in polar regions as well as in lower latitudes, and drew the current systems responsible for the average storm-time variation and for the average disturbance daily variation, separately. Then the complete system of atmospheric currents was determined by combining these two systems. These current systems, though improved, in many respects, compared with the previous system, can explain the observed storm variations only qualitatively.

In order to further improve the current systems on a quantitative basis, he estimated the current intensity at various parts of the systems. The contribution from the secondary currents induced in the earth by the varying magnetic field produced by the outer currents was also taken into account. Thus, in the current systems shown in paper 3, the intensity of electric currents flowing in various parts of the systems was indicated. In the 1938 paper (Vestine and Chapman) some more improvements were made in the quantitative discussions of the average storm field with new observational materials obtained during the Second Polar Year 1932-3.

Though these idealized current systems account for the average characteristics of the observed storm variations fairly well, they refer to a particular epoch, that is, the epoch of the maximum diminution of H in the storm-time variation. It is known however that this variation undergoes rapid changes in the first several hours of the average storm. The disturbance local-time inequality also varies with storm-time in both the amplitude and the phase. In fact, the rates of growth and decay in these two variations were found to be quite different. Hence the atmospheric current systems that can fully explain the average storm-time changes and the average disturbance local-time changes as functions of storm-time, must be determined at various epochs of the storm. It is, of course, not pretended that the magnetic field produced by such hypothetical current systems agrees with the actual storm field in all particulars. It is therefore a different approach to the problem to examine the current systems for individual storms and to compare them with the ideal systems; this latter procedure has been followed, for instance, by Vestine and his colleagues[15], T. Nagata and N. Fukushima[33]. Knowing the average storm changes of the average storm as functions of storm-time, it is possible to construct the current systems that can reproduce the observed fields at various epochs of the storm. The study of such varying current systems during the average magnetic storm is one of the objectives of the present work.

As was already mentioned in (G) of this Section, there is good evidence to believe that the DS variations change considerably with season. The current systems responsible for DS must then vary with season; whereas those for the Dst variations appear to remain relatively constant throughout the three seasons. Therefore, the complete current system for the whole storm-field probably follows a somewhat different course according to season. These questions can be examined by subdividing the material here used.

A remark should be made at this point on the interpretation of the current systems. They are the atmospheric current systems that could give rise to a magnetic field, at the surface of the earth, having the characteristic features of the observed storm field. The current systems afford the simplest means of representing these features of the field, and may be regarded solely as such a means. It is, in principle, not possible to determine the current distribution uniquely, purely from observations of a magnetic field at the earth's surface. This can be illustrated as follows: Observation at the earth's surface of a magnetic field of external origin that is produced by some current system in the atmosphere, enables the potential of the field to be determined in terms of a series of spherical harmonics. Along any radius from the earth's center O the

the gas is shielded from the magnetic field, and the field outside is enhanced. This accounts for the initial phase of the storm, that is, the initial rise in the storm-time field of the horizontal force. On the arrival of the stream near the earth, the mechanical reaction between the electric currents and the earth's magnetic field carves a hollow in the stream: the lateral parts of the stream advance rapidly beyond the earth, so that the hollow becomes very long. Owing to the polarizing influence of the earth's magnetic field, the surface of the hollow is charged, and the surface charges tend to bridge the gap between the negatively and positively charged parts of the stream. This passage across the gap is allowed only at a certain distance from the earth due to the deflection of charges by the earth's field. It is suggested that this bridging is followed by the formation of a ring-current that produces a nearly uniform magnetic field around the earth. This field accounts for the large decrease in the storm-time change in the horizontal force.

H. Alfven[41] has devised a theory of magnetic storms also based on a neutral ionized stream of particles emitted by the sun. The distinctive feature in his theory is that the sun's magnetic field plays an important part in the mechanism of impulsion of charged particles from the sun and in the evolution of the effects in the earth's field. The theory claims to explain many detailed features of aurorae and of the main phase of a magnetic storm, but no explanation is given of the initial phase. Any theory of magnetic storms will encounter great mathematical difficulties, so that idealization of the problem is inevitable. However, whatever the idealization, the premises and the subsequent developments from them, the theory of magnetic storms must explain the observed facts obtained from the analysis of storm data. Hence the knowledge on the morphology of magnetic storms provides a material with which the theory of magnetic storms is guided and is finally tested.

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APPENDIX

Illustration of the treatment of magnetic data on an hour-to-hour difference basis.

The method of analysis adopted in this work has already been shown in Section 5. The following supplements the description given there.

Let us suppose that for a particular storm s, hourly values of element X for the 4 pre-storm hours and the first 72 hours, are given in the observatory record from station S as follows:

storm-time	-4^h	-3^h	-2^h	-1^h	0^h	$1^h \ldots\ldots 71^h$
hourly values X	x_{-4}	x_{-3}	x_{-2}	x_{-1}	x_0	$x_1 \ldots\ldots x_{71}$

Instead of using these hourly values, we take hour-to-hour differences in the following way:

storm-time	-4^h	-3^h	-2^h	-1^h	0^h	$1^h \ldots\ldots 71^h$
hour-to-hour differences	d_{-3}	d_{-2}	d_{-1}	d_0	$d_1 \ldots\ldots d_{71}$	

Here d is defined by

$$d_i = x_i - x_{i-1} \qquad \text{for } i = 0, 1, 2, \ldots, 71$$

$$d_i = x_{i-1} - x_i \qquad \text{for } i = -1, -2, -3.$$

These hour-to-hour differences are entered in Table A in the corresponding columns in row s.

Let the mean variation of the five international quiet days of the month in which storm s occurred, be expressed by the hourly values (for the storm-time hour indicated by the subscripts)

$$Q_0, Q_1, Q_2, \ldots\ldots, Q_{22}, Q_{23} (= Q_{-1});$$

thus Q_0 refers to the hour closest to the sudden commencement of this storm. From these hourly values, hour-to-hour differences are taken as follows:

$$q_0\ (= Q_0 - Q_{-1}),\ q_1\ (= Q_1 - Q_0),\ \ldots\ldots,\ q_{23}\ (= Q_{23} - Q_{22}).$$

These Sq-differences are entered in Table B in row s in the hourly columns corresponding to the subscripts of the q's.

Then for each storm, q_i ($i = 0, 1, 2, \ldots\ldots, 23$) was subtracted from d_{24n+i} ($n = 0, 1, 2$; $i = 0, 1, 2, \ldots\ldots, 23$) for the same subscript i, where n refers to (storm) day 0, 1, 2. Let the remainder so obtained be denoted by $r_0, r_1, r_2, \ldots\ldots, r_{71}$. For three pre-storm hours Sq-differences are measured backwards as in d. That is,

$$\begin{aligned} q_i &= Q_{i-1} - Q_i \\ &= Q_{24+(i-1)} - Q_{24+i} \\ &= -q_{24+i} \qquad i = -1, -2, -3. \end{aligned}$$

Therefore, the corresponding r's are

$$\begin{aligned} Y_i &= d_i - q_i \\ &= d_i + q_{24+i} \qquad i = -1, -2, -3. \end{aligned}$$

Summarizing, we have for r_i ($i = -3, -2, -1, 0, 1, \ldots\ldots, 71$)

$$r_{-3},\ r_{-2},\ r_{-1},\ r_0,\ r_1,\ \ldots\ldots,\ r_{71}.$$

These are entered in Table C in the corresponding columns in row s. When there are missing entries in Table A, the corresponding entries in Table C are left blank.

Means are taken of the 75 columns in Table C. Let us denote these means by

$$\bar{r}_{-3},\ \ldots\ldots,\ \bar{r}_{-1},\ \bar{r}_0,\ \bar{r}_1,\ \ldots\ldots,\ \bar{r}_{71}.$$

Then, clearly the Dst variation for element X is given by a series of values:

$$X_i = \sum_{j=0}^{i} \bar{r}_j, \qquad j = 0, 1, \ldots\ldots, i;\ i = 0, 1, 2, \ldots\ldots, 71.$$

For -4^h, -3^h, -2^h, we have

$$X_{-i} = \sum_{j=1}^{i-1} \bar{r}_{-j} \qquad j = 1, 2, \ldots\ldots, i-1;\ i = 2, 3, 4.$$

Now, we proceed to form Table D. We first consider H for the first 6-hour interval (0^h-5^h). Let us take the part of Table C for H for storm-times 0^h to 5^h. The transcription from storm-time Table C to local-time Table D is illustrated by taking a row, say, row s. In this row we have $r_0^{(s)}$, $r_1^{(s)}$, ..., $r_5^{(s)}$. The local times, to which these values refer, are of course known. Let us suppose that $r_0^{(s)}$ refers to local time t_l. Then, we enter the following quantities in Table D in the corresponding (local-time) columns in row s:

local time	t_ℓ	$t_{\ell+1}$	$t_{\ell+2}$	$t_{\ell+3}$	$t_{\ell+4}$	$t_{\ell+5}$
	$r_0^{(s)}-\bar{r}_0$	$r_1^{(s)}-\bar{r}_1$	$r_2^{(s)}-\bar{r}_2$	$r_3^{(s)}-\bar{r}_3$	$r_4^{(s)}-\bar{r}_4$	$r_5^{(s)}-\bar{r}_5$

All the values in this interval (in Table C) are transferred to Table D in this way after the mean Dst-differences are subtracted.

For the second to the eighth 6-hour intervals, and for three 8-hour intervals in the third (storm) day, the procedure for H is the same as for the first 6-hour interval, except that the mean Dst-differences are not subtracted. For D and V, the mean Dst-differences are not subtracted for any of the intervals, because Dst for these elements is so small.

After Table D is formed for each interval for each element, the means are taken of each column. Let us denote these means by u_0, u_1, u_2, ..., u_{23}, the subscripts referring to local times. From each u the mean of these twenty-four u's was subtracted. That is

$$u_0' \ (=u_0-\bar{u}),\ u_1' \ (=u_1-\bar{u}),\ \ldots\ldots,\ u_{23}' \ (=u_{23}-\bar{u}).$$

Here, $\bar{u}$ corresponds to the mean Dst (on an hour-to-hour basis) for the interval under consideration, except for the first 6-hour group for H.

We form a series of values

$$u_0'' \ (=u_0'),\ u_1'' \ (=u_0'+u_1'),\ u_2'' \ (=u_0'+u_1'+u_2'),\ \ldots\ldots,\ u_{23}'' \ (=u_0'+u_1'+\cdots+u_{23}'),$$

that is,

$$u_i'' = \sum_{j=0}^{i} u_j' \qquad j = 0, 1, 2, \ldots\ldots, i; \ i = 0, 1, 2, \ldots\ldots, 23.$$

Then, it is clear that the disturbance local-time inequality u_i^* is given by

$$u_i^* = u_i'' - \overline{u''}$$

where

$$\overline{u}'' = \frac{1}{23} \sum_{i=0}^{23} u_i''.$$

The sequence u_i^* thus represents DS.